



**Integrity ★ Service ★ Excellence**

# **MECHANICS OF MULTIFUNCTIONAL MATERIALS & MICROSYSTEMS**

9 March 2012

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AFOSR/RSA  
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<b>SECURITY CLASSIFICATION OF:</b> <table border="1"> <tr> <td>a. REPORT <b>unclassified</b></td> <td>b. ABSTRACT <b>unclassified</b></td> <td>c. THIS PAGE <b>unclassified</b></td> </tr> </table>			a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>	<b>LIMITATION OF ABSTRACT</b> <b>Same as Report (SAR)</b>	<b>NUMBER OF PAGES</b> <b>50</b>	<b>NAME OF RESPONSIBLE PERSON</b>
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# 2012 AFOSR SPRING REVIEW



**NAME:** B. L. ("Les") Lee

## **BRIEF DESCRIPTION OF PORTFOLIO:**

***Basic science for integration of emerging materials and micro-devices into future Air Force systems requiring multi-functional design***

## **LIST OF SUB-AREAS:**

***Fundamentals of Mechanics of Materials;***

***Life Prediction (Materials & Micro-devices);***

***Sensing, Detection & Diagnosis;***

***Multifunctional Design of Autonomic Systems;***

***Multifunctional Design of Reconfigurable Systems;***

***Self-Healing & Remediation;***

***Self-Cooling & Thermal Management;***

***Energy Management for Self-Sustaining Systems;***

***Actuation & Threat Neutralization;***

***Engineered Nanomaterials***



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*Actuation & Threat Neutralization;* ↗

*Engineered Nanomaterials* ↘



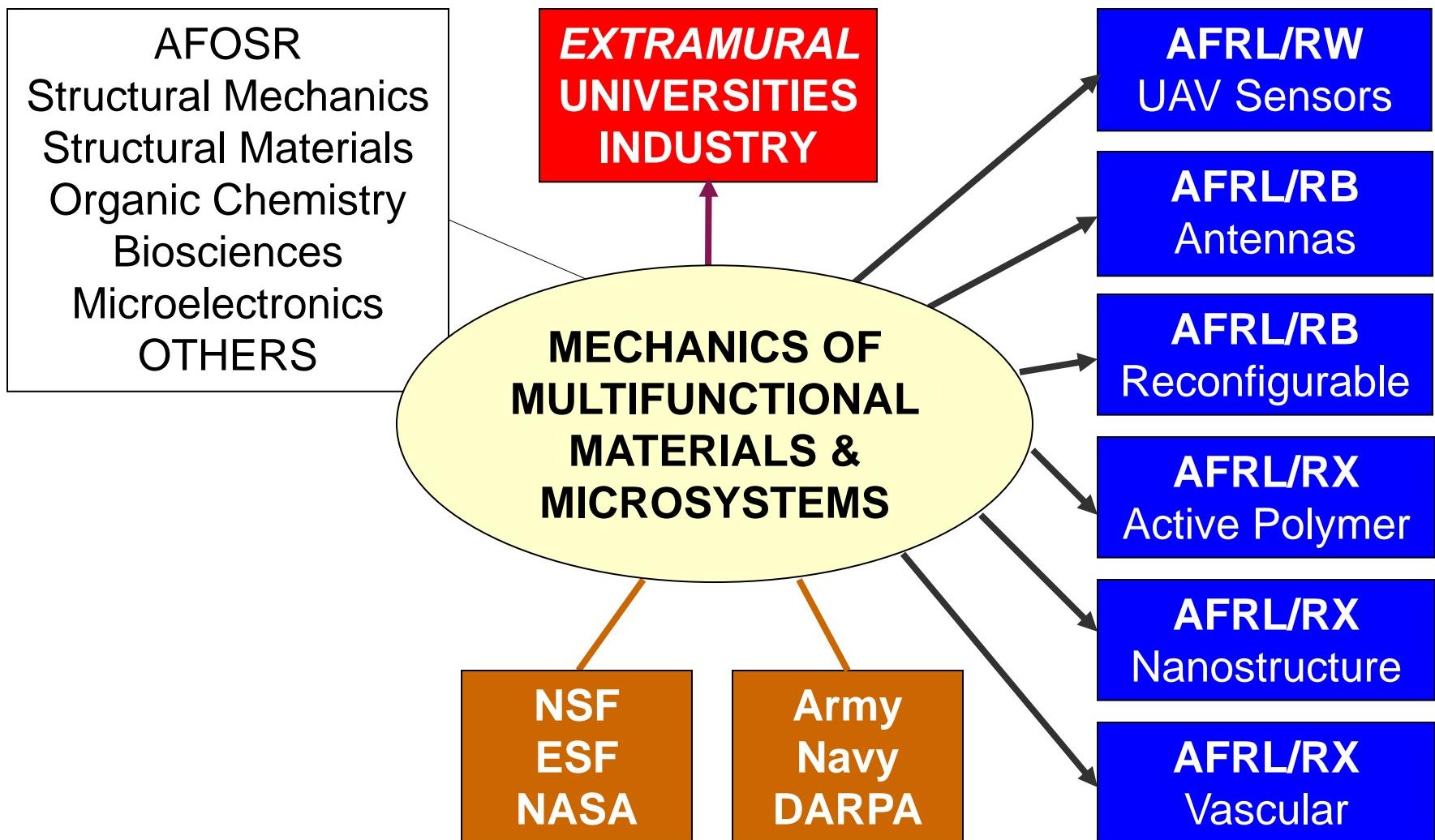
# SCIENTIFIC CHALLENGE



- **Self-healable or in-situ remendable structural materials** (*1<sup>st</sup>-ever program; world lead*)
- Microvascular composites for **continuous self-healing** and **self-cooling systems** (*1<sup>st</sup>-ever program; world lead*)
- Structural integration of **energy harvest/storage capabilities** (*1<sup>st</sup>-ever program on structurally integrated multiple energy harvest capabilities; DoD lead*)
- Neurological system-inspired **sensing/diagnosis/actuation network** (*pot'l world lead*)
- Mechanized material systems and micro-devices for **reconfigurable structures** (*DoD lead*)
- **Experimental nano-mechanics** (*DoD lead*)
- **Active materials for threat neutralization** (*planned*)

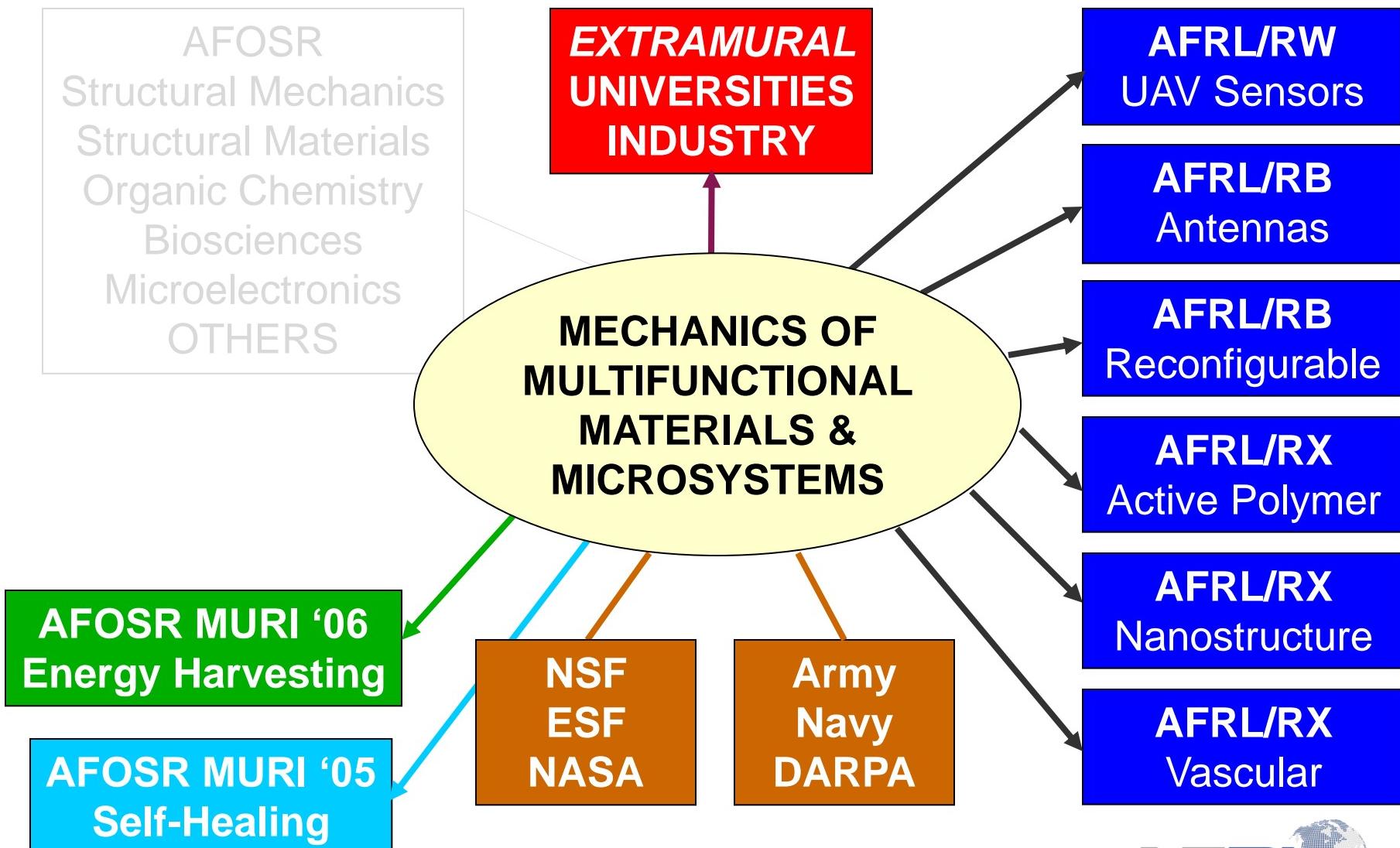


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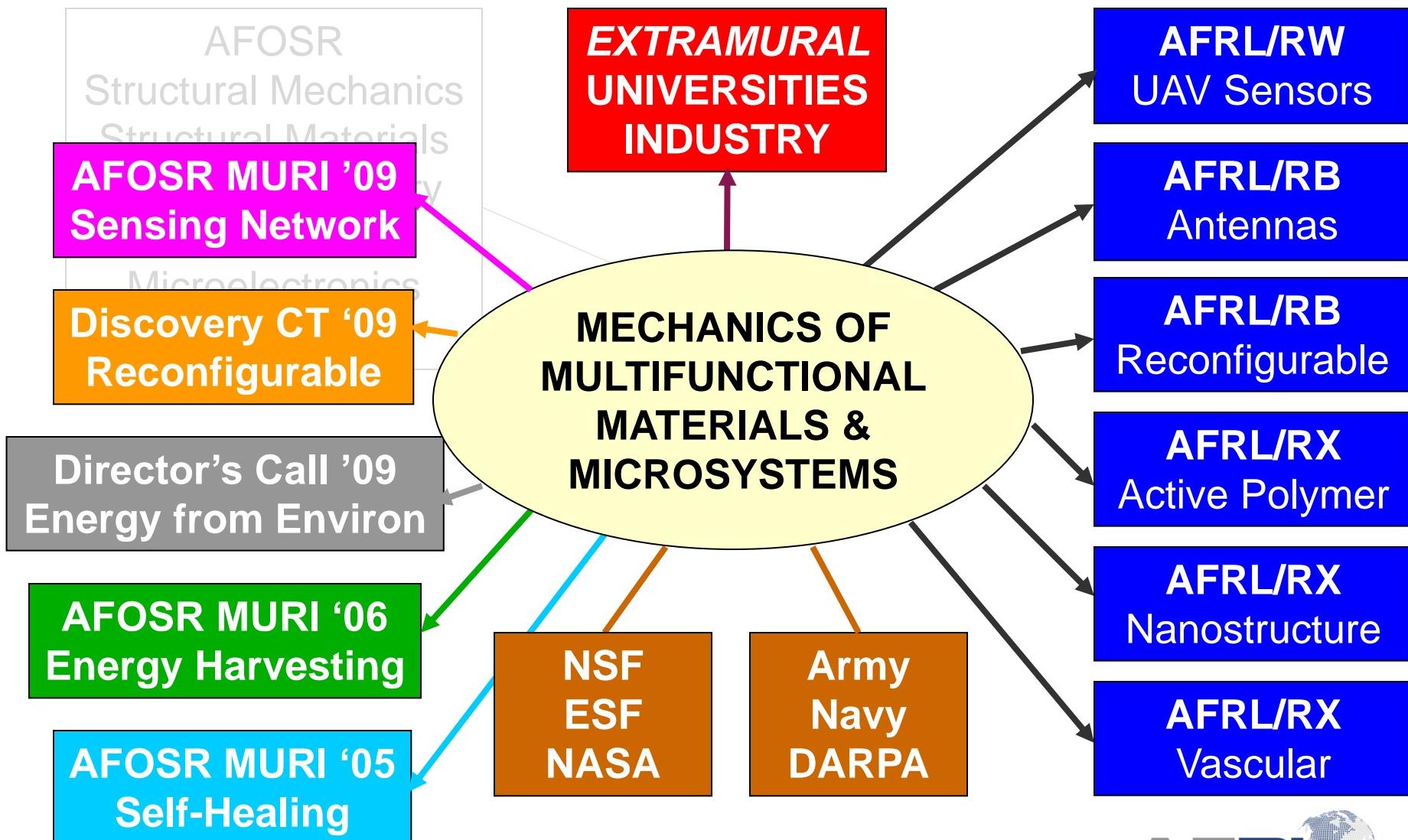


# PROGRAM INTERACTION



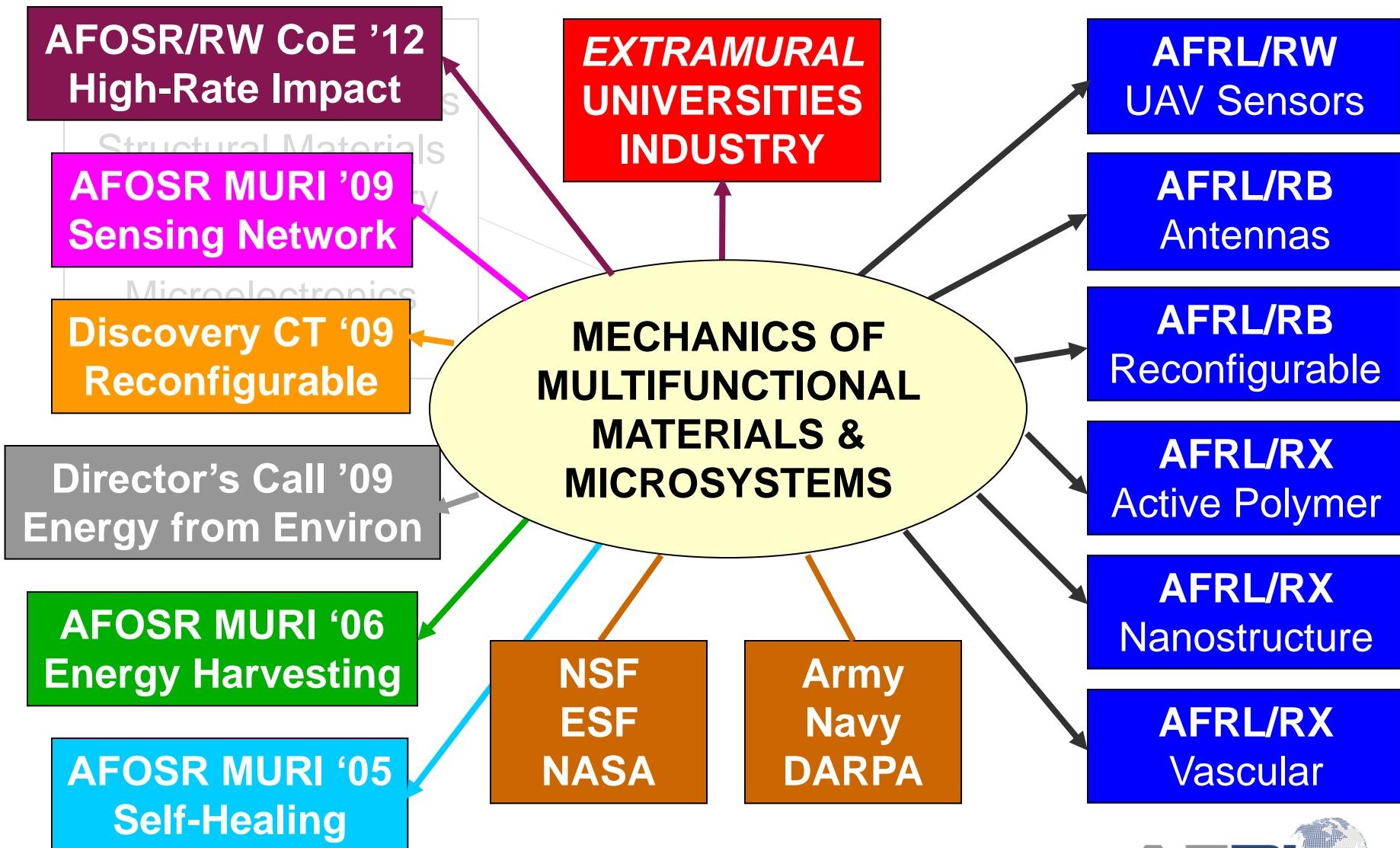


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## **PI's & Co-PI's:**

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**Ioannis Chasiotis (UIUC)**  
**David Kisailus (UC Riverside)**  
Pablo Zavattieri (Purdue U)  
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Michael Ortiz (Caltech)\*  
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Greg Carman (UCLA)\*

<sup>▲</sup> YIP; \* CoE



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Actuation

Engineered

## Subject:

- < **Multi-scale Simulation of Interfacial Phenomena Deformation & Fracture of Silicon for MEMS**
  - > **Damage-tolerant Biological Composites**
  - > **Designing Structures for Functional Materials**
  - > **High-rate Physics of Heterogeneous Materials**

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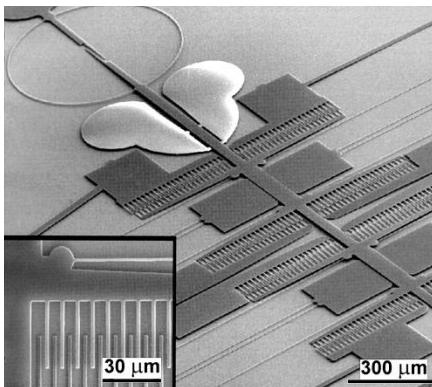


# FRACTURE OF MEMS MATERIALS (UIUC: Chasiotis)

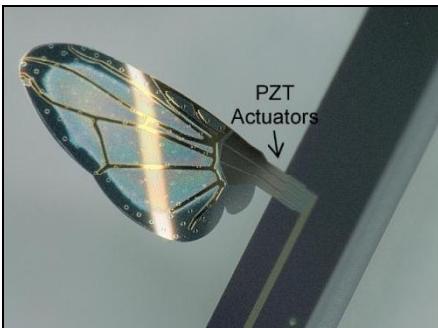


## Polycrystalline silicon is most widely used for MEMS

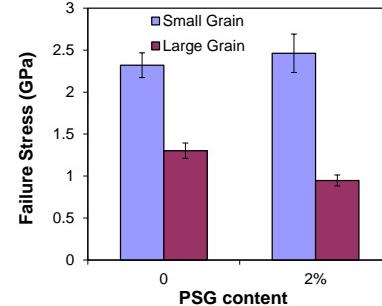
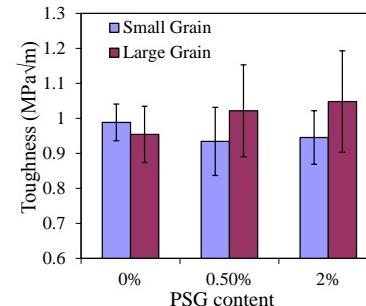
- Experiments (bi-crystal Chevron) show the role of **grain structure** in fracture of polysilicon.
- Fracture of polysilicon is **intragranular** due to high grain boundary strength.



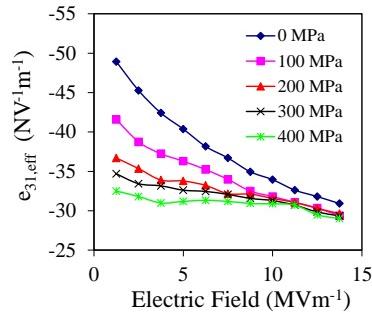
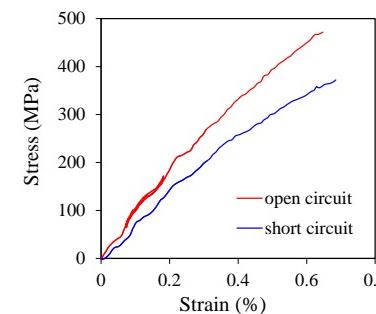
## PZT thin film bimorph actuates a millimeter scale wing for MAV



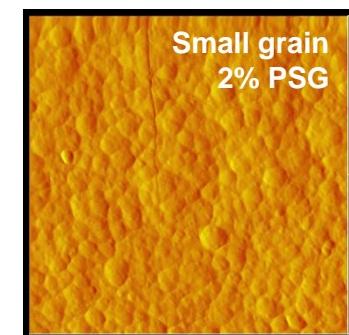
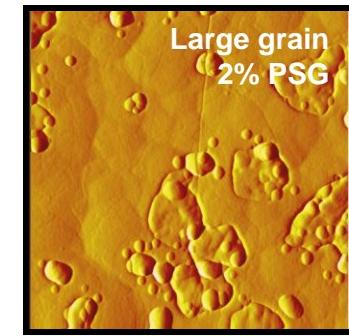
- Mode I fracture toughness of **large grain polysilicon** increased with the amount of Phosphorus **doping**. Dopants at grain boundaries may allow for **local crack deflection**.
- The fracture strength of "**laminated small grain polysilicon**" **was 80-150% higher** than large grain polysilicon with doping playing a secondary role in fracture strength. Fabrication of polysilicon in laminate form reduced the **flaw size** significantly.



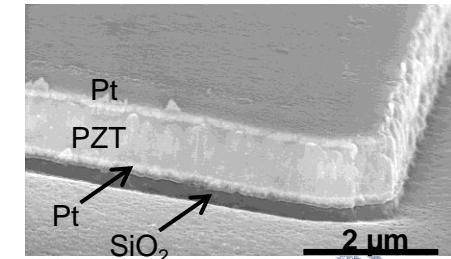
- The modulus and tensile strength of **PZT films** for MEMS were measured for the first time. They were **30% smaller under short circuit conditions** as opposed to open circuit conditions.
- The high bias voltage **electroactive coefficient** varied nonlinearly with the electric field, but it **became independent of the applied field at high pre-stress values**.



## Polycrystalline Silicon



## PZT Composites





# AFOSR/RW CO-SPONSORED COE'12 (RW: Chhabildas)



**University Center of Excellence:**  
**High-Rate Deformation Physics of Heterogeneous Materials**  
California Institute of Technology & University of California, Los Angeles

**Goals:**

- Develop a fundamental understanding of the deformation physics of heterogeneous materials at **high-strain-rates** and **high-pressure**s
- Develop **microstructures** and **functional nano-materials** for mitigating shock and damage
- Use innovative methods for **educating** and **training** the next generation of scientists and practitioners

The diagram illustrates the research cycle and experimental setup. On the left, a circular flow diagram shows the integration of Materials science, Shock physics, and Computational science through Theory, Multiscale modeling, and Mesoscale experiments. Key figures include Bhattacharya, Ortiz, Andrade, Ortiz, Carman, Daraio, Lynch, and Ravichandran. The center features a schematic of a high-speed impact experiment using a grating and 3D DIC for imaging. On the right, a large orange circle represents the 'CENTRAL THEMES' of High Rate Deformation Physics of Heterogeneous Materials, encompassing Shock Physics, Materials, and Modeling & Simulation, with focus areas like Mesoscale Experiments, Functional Materials, and Theory GEM, OTM.

**PI & Co-PI's:**

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**Erik Thostenson (U Del)**▲

**Akira Todoroki (Tokyo Tech)**

**fu-Kuo Chang (Stanford U)**\*

**Xian Wang (Stanford U)**\*

**Boris Murmann (Stanford U)**\*

**Philip Levis (Stanford U)**\*

**Andrew Ng (Stanford U)**\*

**Robert McLeod (U CO)**\*

**Greg Carman (UCLA)**\*

**Yong Chen (UCLA)**\*

**Somnath Ghosh (Ohio St U)**\*

**Rahmat Shoureshi (NYIT)**\*

**Frank Ko (U Brit Columbia)**\*

**Jeff Baur (AFRL/RXBC)**

**Ben Dickinson (AFRL/RWGN)**

**Greg Reich (AFRL/RBSA)**

**Yakup Bayram (PaneraTech)**+

**Rob Bortolin (NextGen)**+

**Francesca Scire (Phys Sci)**+

▲ YIP; \* MURI; + STTR



# 2012 AFOSR SPRING REVIEW



NAME: B. J. ...

BRIEF DESCRIPTION:

Basic science research into future technologies

LIST OF SUBJECTS:

Fundamental

Life Prediction

Sensing, Detection

Multifunctional

Multifunctional

Self-Healing

Self-Cooling

Energy Management

Actuation

Engineered

Materials

Design

**Subject:**  
*Electromagnetically Tunable Fluids*  
*Thermal Signature Reduction & EMI Shielding*  
  < *Nanocomposites for Sensing & Actuation*  
*Damage Detection w Time Domain Reflectometry*  
*Bio-inspired Intelligent Sensing Materials*

*Embedded Sensors & Actuators for MAV*

“

“

“

> *Load-Bearing Antennas of Conductive Textiles*

“

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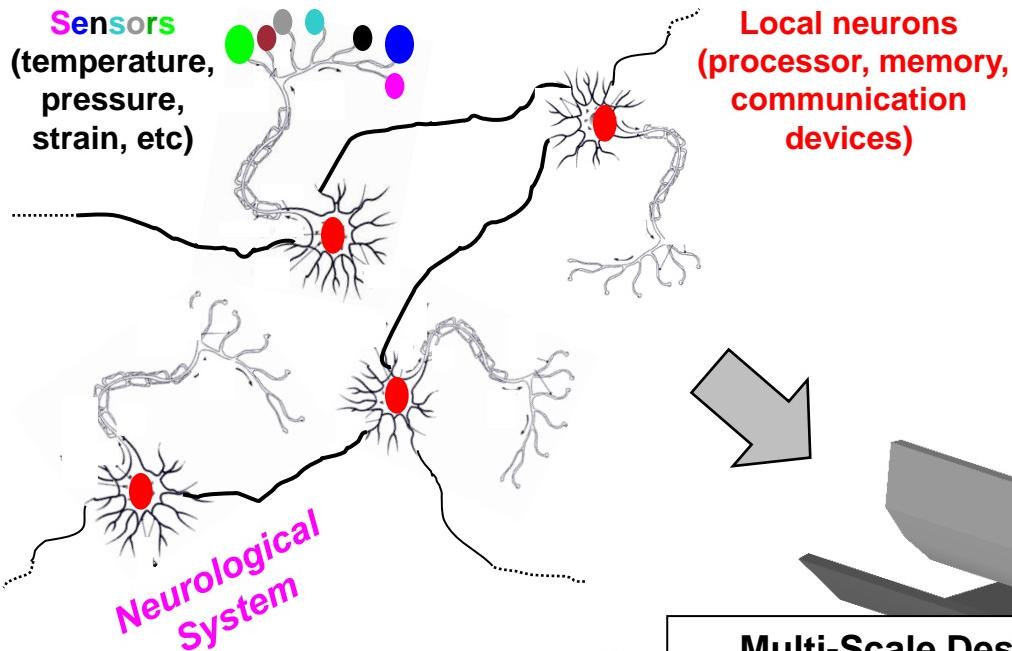
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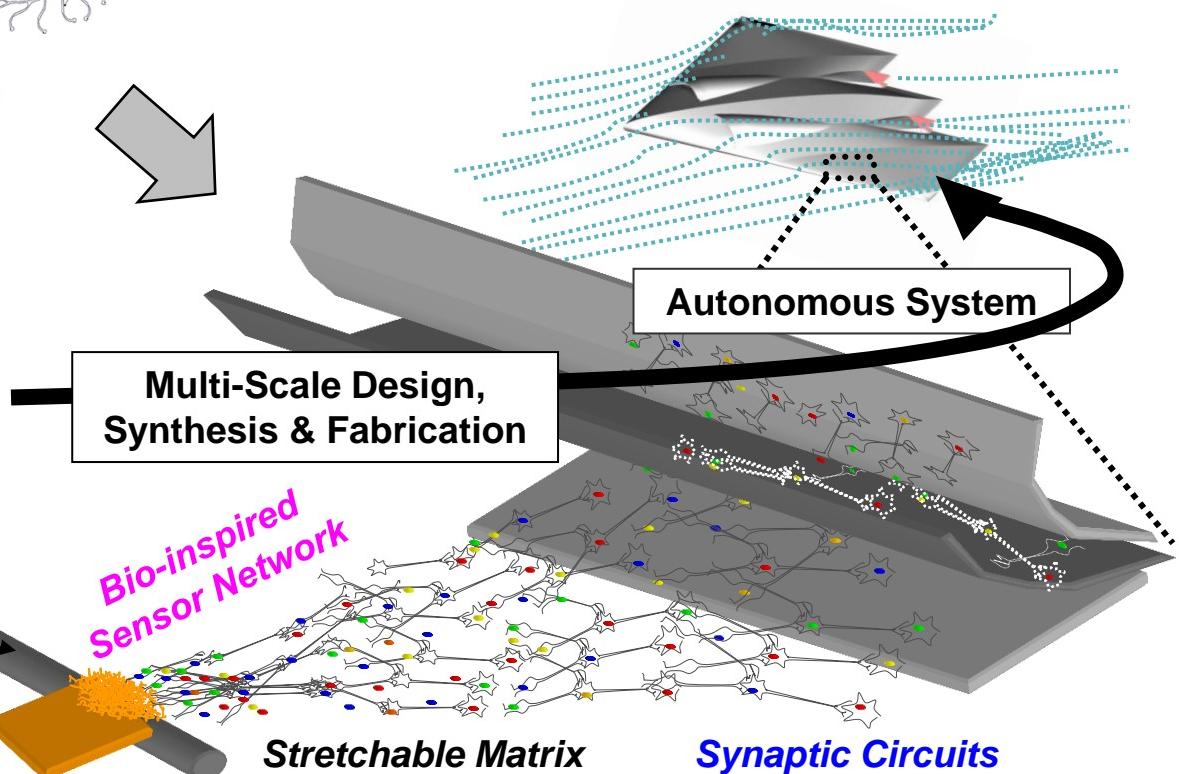
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# BUILT-IN SENSING NETWORK (Stanford/U CO/UCLA/NYIT: Chang)



**Synapse:**  
Cognition and decision-making are determined by a relative level of cumulative signal strength with respect to the synapse threshold values



Biological sensory systems rely on **large numbers of sensors distributed over large areas** and are specialized to detect and process **a large number of stimuli**. These systems are also capable to **self-organize** and are **damage tolerant**.

# Sensor Network for Structural Integration



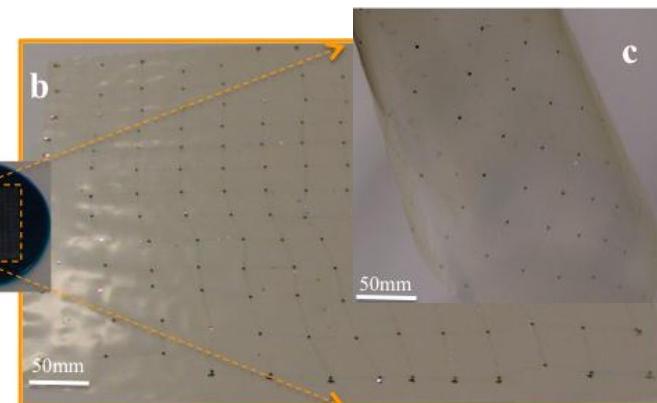
## Task 1: Sensor Network for Structural Integration

To develop a nano/micro-scaled sensor network, functionalize the network to a macro scale, and integrate the sensor network into composite materials.

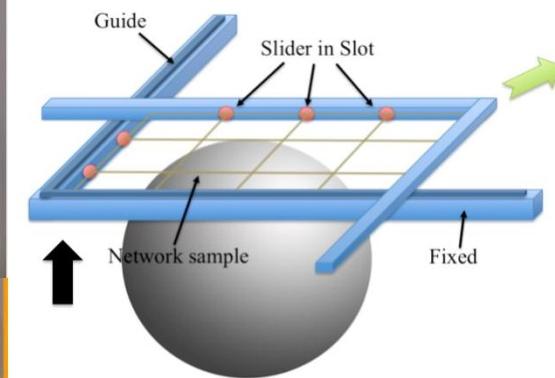
### Chang's group

To develop **PZT sensor network** in a CMOS-like foundry:

- Scaled down sensor network to **reduce wire & node size** (for higher spatial resolution).
- Developed spin-coated-on process for **network fabrication**.
- Developed a design method for **network expansion**.



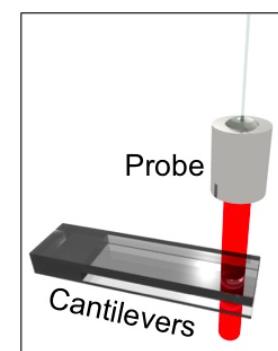
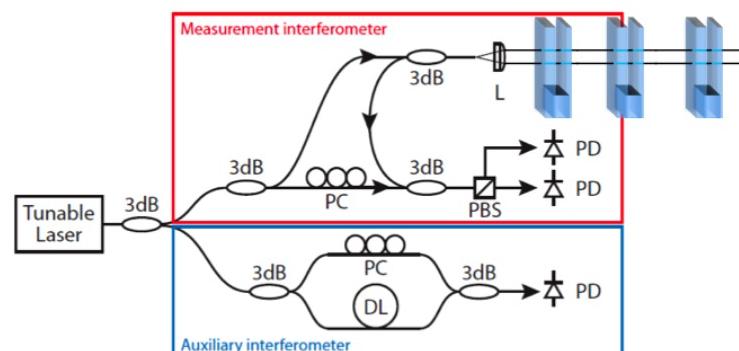
13 by 13 stretchable temperature sensor network



### McLeod's group

To develop ultra-precise **polymer optical sensor network** via **liquid deposition photolithography**:

- Deposition of polymer from the liquid state enables tightly integrated optical sensors.
- Atomic-scale precision: **0.53 nm**
- Interrogates thousands of sensors through **round-trip delay** to each partially-reflecting surface.



# Micro/Nano Sensors for State Awareness

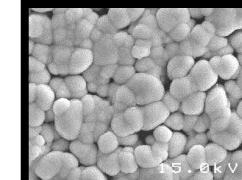
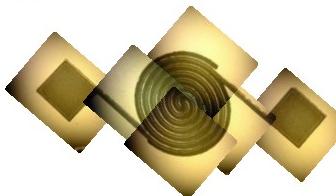


## Task 2: Micro/Nano Sensors for State Awareness

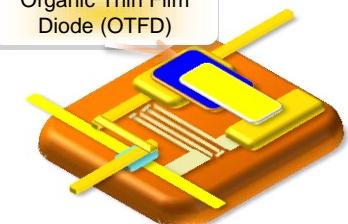
To develop multi-physics multi-scale sensors for state awareness with an ease of network integration.

### Chang's group:

- Screen-printing **PZT sensors** onto a network
- Integrated **organic thin film diodes** into sensor network

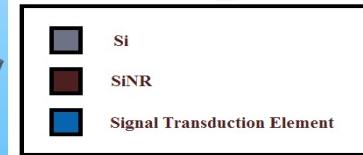
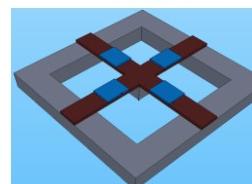
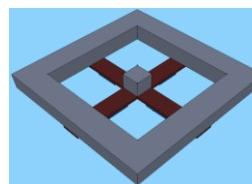


Organic Thin Film Diode (OTFD)



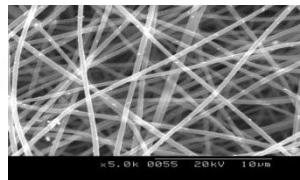
### Wang's group:

- Designed an **air flow sensor** measuring the direction and the velocity.
- Used four anisotropic **magnetostriuctive structures** to transduce an air flow-induced beam deflection into a resistance change.

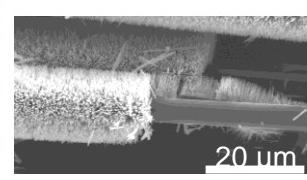


### Ko's group:

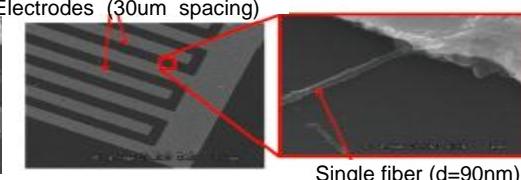
- Developed multi-functional **nanofibers** that can serve as: **magnetic, piezoelectric and chemical sensors**



Magnetic nanofibers



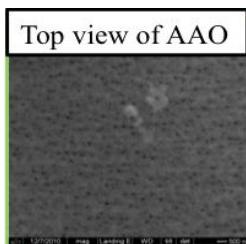
Piezoelectric fibers



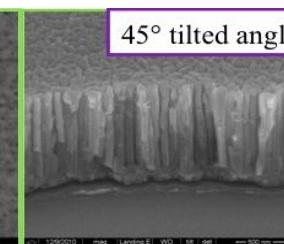
Nanofiber-based chemical sensors

### Carman's group:

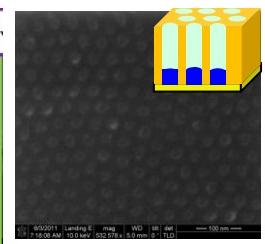
- Investigated nano-structured **magneto-electric** materials for detecting **magnetic fields**.
- 40 and 25 nm diameter Ni nanostructures fabricated using AAO and DBC nanotemplate respectively.



Top view of AAO



45° tilted angle



DBC Polymer template

### McLeod's group:

- A new approach to **optical sensor** interrogation.

# Bio-inspired Neuron Circuits & Interface Electronics



## Task 3: Bio-inspired Neuron Circuits and Interface Electronics

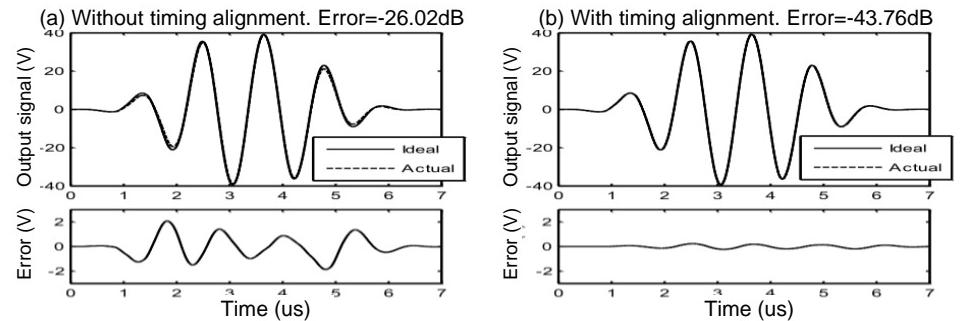
To develop bio-inspired neuron circuits with appropriate electronics to interface with various sensors.

### Murmann's group

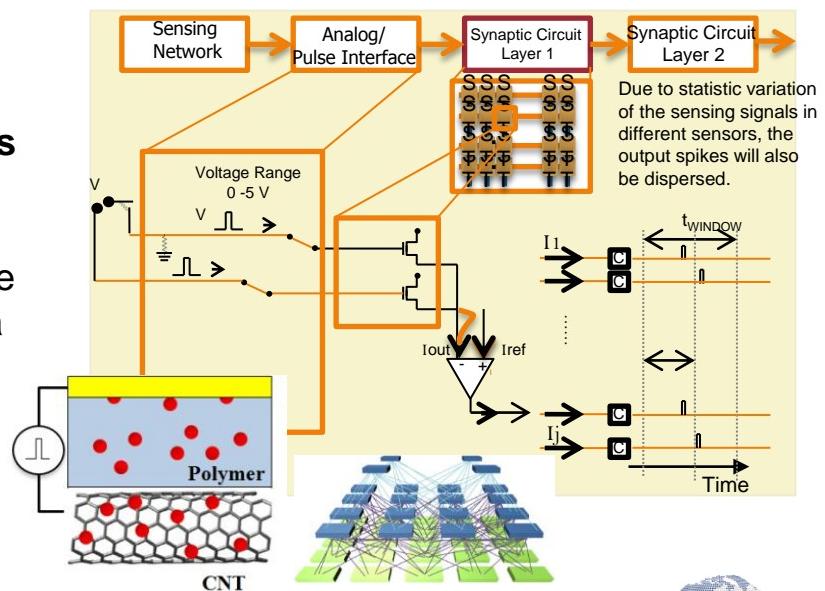
- Built a dense **integrated interface circuit** for ultrasonic sensing of the structural state.
- Defined **piezo driver** test chip to deliver a high voltage, high freq, continuous-time waveform.
- Plans to integrate piezo sensing interface with piezo driver on a **single chip**.

### Chen's group

- Invented **synaptic transistors** with dynamic logic, memory, and learning functions by integrating ions in CNT/polymer composites.
- Voltage pulses can induce the **electrochemical reactions between ions and CNTs**, modifying the conductivities of CNTs reversibly for learning and memory functions.
- A **neuron circuit** with a large number of **synapses** can be fabricated by integrating an analog Si-CMOS circuit and a randomly connected CNT network in polymer composite.
- Integrated the first time the **synaptic transistors** with a **stretchable network** (from Chang's group) to process signals from an array of **temperature sensors**.
- Demonstrated that the integrated circuits can process the **temperature profile** dynamically.



Output signals of the piezo-element driver without (left) and with (right) timing alignment





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**Nancy Sottos (UIUC)**

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Jeffrey Moore (UIUC)

**Nicolaus Correll (U CO)**

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Philippe Geubelle (UIUC)\*

Kenneth Christensen (UIUC)\*

Jonathan Freund (UIUC)\*

**Jeff Baur (AFRL/RXBC)**

**Tom Darlington (Nanocomposix)+**

Tony Starr (SensorMetrix)+

\* **MURI**; + **STTR**



# 2012 AFOSR SPRING REVIEW



NAME: B. A.

BRIEF DESC:

Basic science  
into future

LIST OF SU:

Fundamen

Life Predic

Sensing, D

Multifuncti

Multifuncti

**Self-Healing**

Self-Coolin

Energy Ma

Actuation

Engineered

## Subject:

< **Thermally Remendable Composites**  
**Interfacial Self-Healing in Composites**  
**Regeneration & Remodeling of Composites**

> **Self-Assembly and Self-Repair of Structures**  
    < **Microvascular Autonomic Composites**

< **Processing of Microvascular Structures**  
**Remendable Composites w Resistive Heating**

> **New**; < **Concluded**

## PI's & Co-PI's:

**Sia Nemat-Nasser (UC San Diego)**

**Nancy Sottos (UIUC)**

**Scott White (UIUC)**

Jeffrey Moore (UIUC)

**Nicolaus Correll (U CO)**

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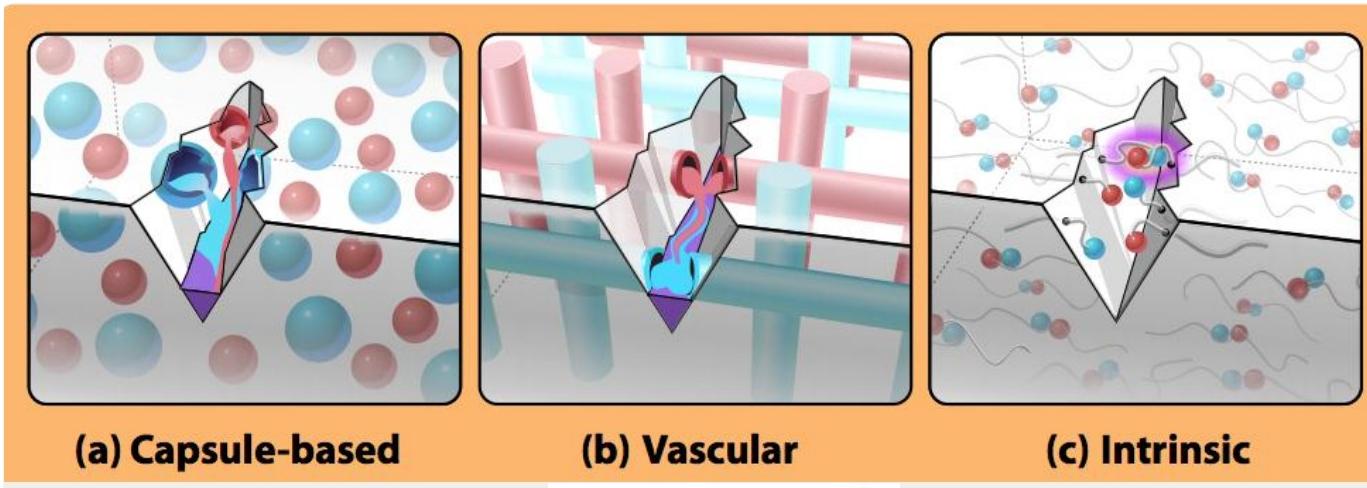
**Tom Darlington (Nanocomposix)+**

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\* **MURI**; + **STTR**

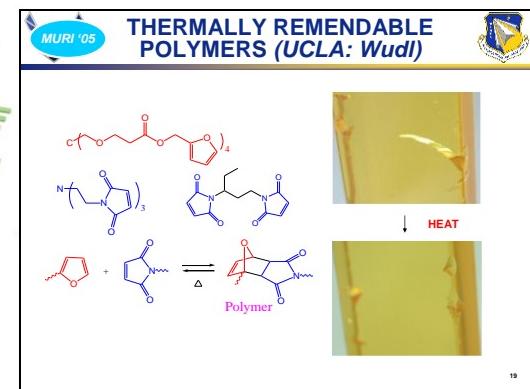
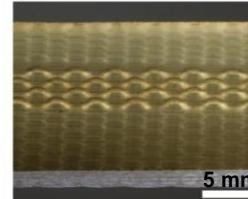
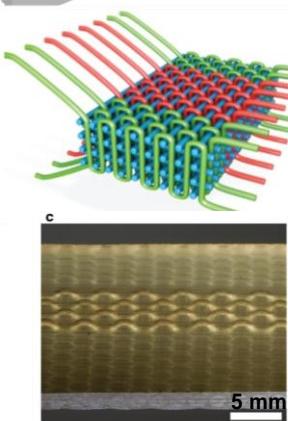
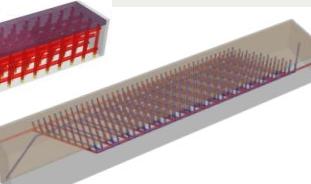
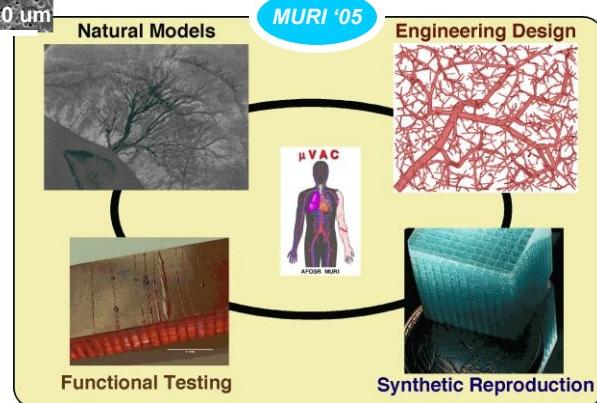
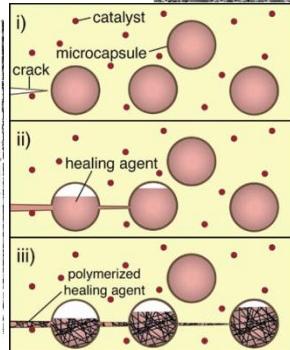


# THREE APPROACHES FOR SELF-HEALING



The Washington Post

## Nature





# STRUCTURAL REGENERATION (UIUC: White/Moore)



## Regeneration and Remodeling in biology:

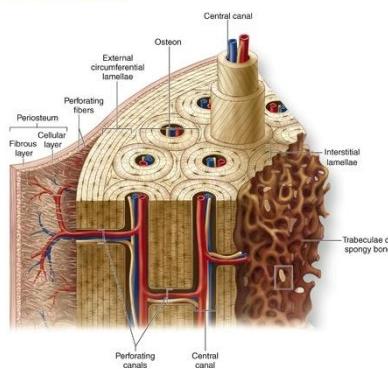
Tree skink lizard



Linckia starfish



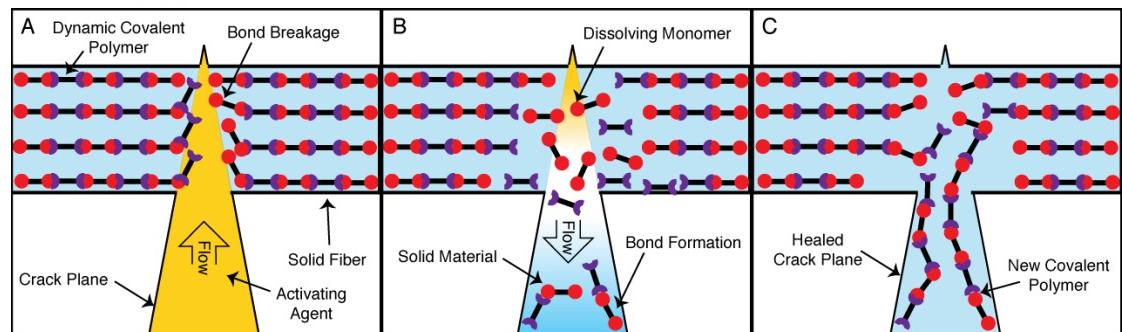
Human Bone



## Conventional Material Systems:

- Passive materials not responsive to degradation
- Not adaptive to loading conditions
- Manual repair of damage
- Overdesign to account for reduction in mechanical properties and varied loading conditions

## New approach: *Dynamic polymers + inert scaffolds*



- Synthesized two types of **dynamic covalent bond based polymer** systems which can be **reversibly changed from liquid to solid and vice versa**
- **Poly(vinyl alcohol)** and **borate ions** undergo multiple **sol-gel** transitions under controlled pH
- **Reversible gel formation** of a functionalized poly(ethylene glycol) and crosslinker

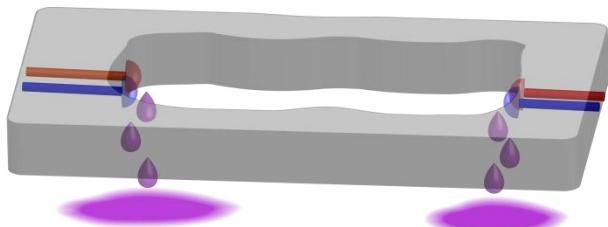


# STRUCTURAL REGENERATION: *Large Volume Damage*

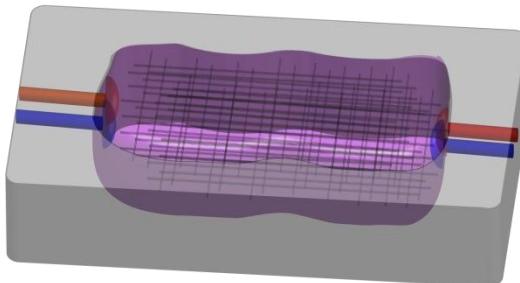


## Background:

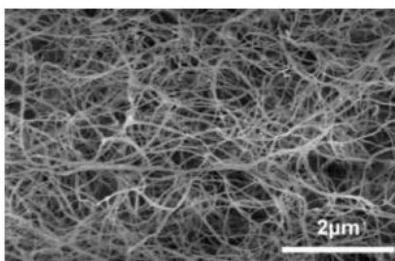
- Repair volume is limited by surface tension



- Self-assembled scaffolds** will provide temporary support as healing agents delivered



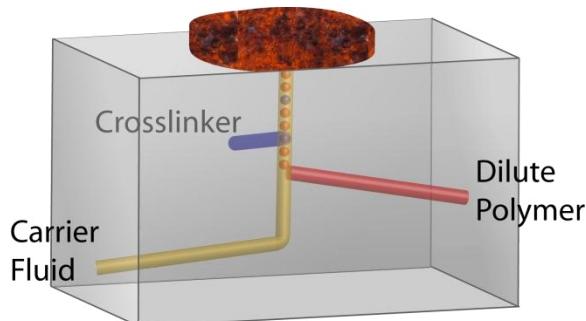
Scaffold-supported  
damage region



Peptide Amphiphile  
Self-assembling Fibers

## Progress:

- Sol-Gel transition** allowed three orders of magnitude stiffness increase
- Scaffold formation based on **peptide amphiphile hydrogels** is repeatable for multiple cycles
- Aggregate scaffolds formed by **hydrogen, covalent or ionic bonds** in progress
- Isolated constituents delivered via **vascular network**





# 2012 AFOSR SPRING REVIEW



NAME: B. L. ("Les") Lee

## BRIEF DESCRIPTION OF PORTFOLIO:

*Basic science for integration of emerging materials into future Air Force systems requiring multi-functionalities*

## LIST OF SUB-AREAS:

*Fundamentals of Mechanics of Materials;*

*Life Prediction (Materials & Micro-devices);*

*Sensing, Detection & Diagnosis;*

**Multifunctional Design of Autonomic Systems;**

*Multifunctional Design of Reconfigurable Systems;*

*Self-Healing & Remediation;*

**Self-Cooling & Thermal Management;**

*Energy Management for Self-Sustaining Systems;*

*Actuation & Threat Neutralization;*

*Engineered Nanomaterials*

## **PI's & Co-PI's:**

**Abraham Stroock (Cornell U)**

Noel Holbrook (Harvard U)

**Vikas Prakash (Case Western)**

**Patrick Kwon (Mich St U)**

**George Lesieutre (Penn St U)**

**Aaron Esser-Kahn (UC Irvine)** ^

**Scott White (UIUC)**\*

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**Ajit Roy (AFRL/RXBT)**

^ YIP; \* MURI



# 2012 AFOSR SPRING REVIEW



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Self-Heal

Self-Cool

Energy M

Actuation

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## Subject:

### *Plant-mimetic Heat Pipes*

< CNT Based Thermal Interface Materials

New Generation of Perspirable Skin

Variable Thermal Conductivity Structures

> Microvascular Systems for Mass/Energy Transport

< Microvascular Autonomic Composites

**Carbon Fiber Morphology for Thermal Materials**

> New; < Concluded

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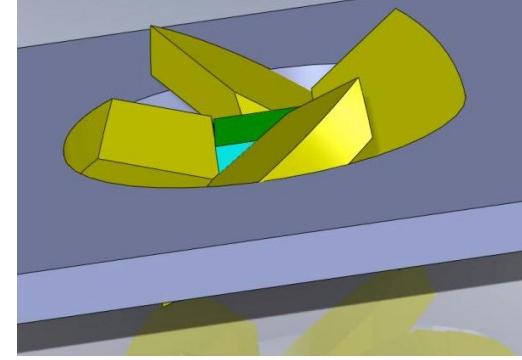
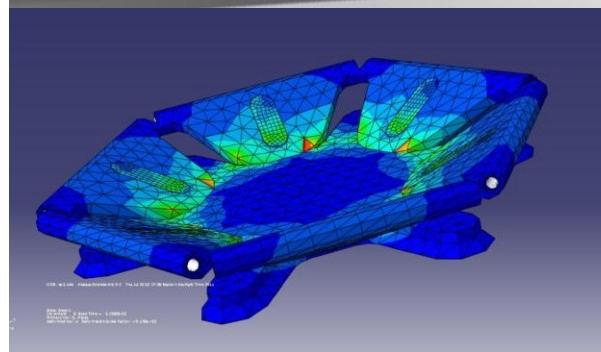
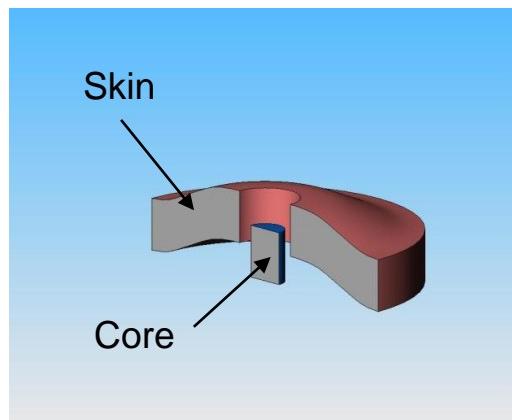
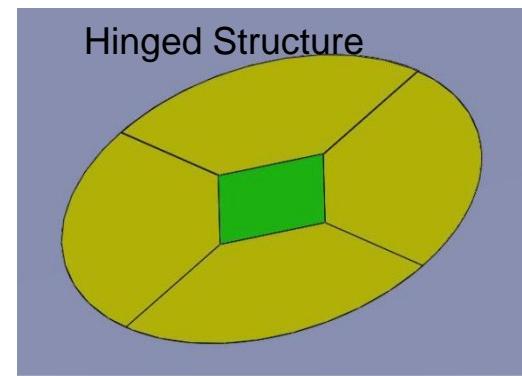
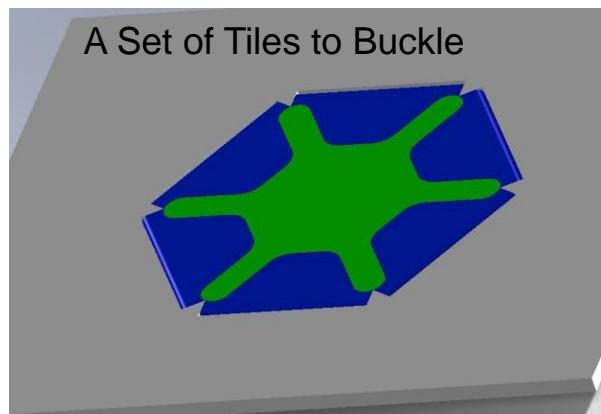
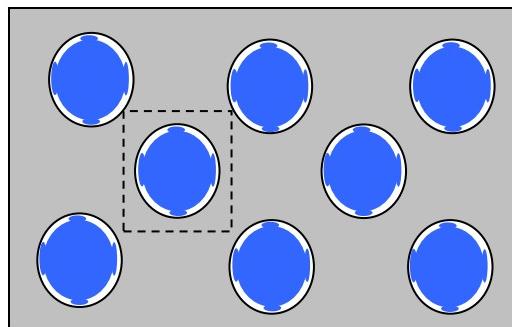
^ YIP; \* MURI



# PERSPIRABLE SKIN OF CERAMICS (*Mich State U: Kwon*)



- **Approach (I): Deformable materials under thermal loading** (The interference between two distinct materials that has been shrink-fitted opens for cooling; gap is not large enough)
- **Approach (II): A set of tiles to buckle under thermal loading** (Upon heating, the tiles push on the core radially, while shrinking circumferentially, enabling a buckling action)
- **Approach (III): A hinged structure triggered by internal pressure** (The assembly consists of the skin (rectangular part), two half circular tiles, and two axes to provide a rotation)





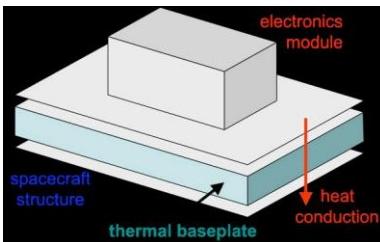
# THERMAL BASE PLATE DESIGN

## (Penn State: Lesieutre)

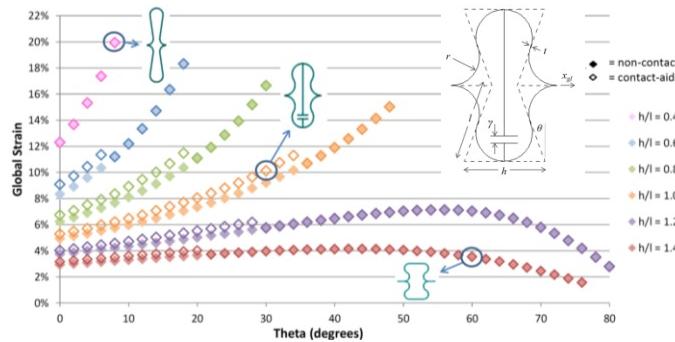


### Need for Material Systems with Variable Thermal Conductivity

- Electronic modules are designed to operate near room temperature and they generate significant heat loads. They are connected to the spacecraft bus structure via a **thermal base plate** which is intrinsically **multifunctional**.
- The thermal base plate transfers **mechanical load** and transfers **heat** away from (or insulates) the electronics module in order to ensure that the electronics do not overheat (or become too cold).



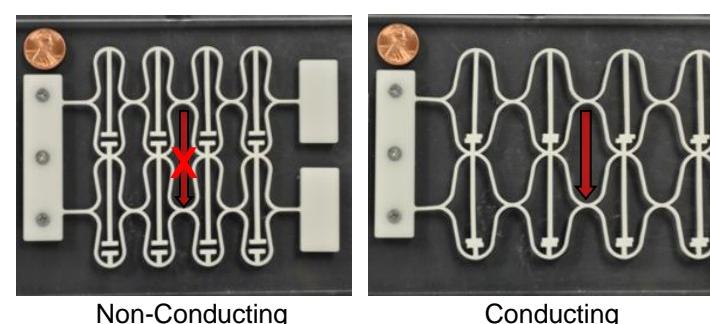
- Active and passive **thermal switches** exist, and passive ones are preferred for low power and complexity.



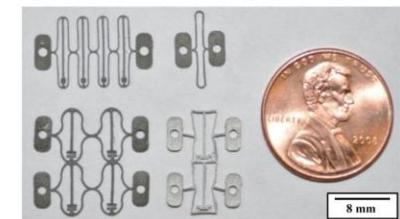
Global strain vs. Cell angle parameter

### Cellular Contact-aided Compliant Mechanisms (C3M):

- C3M allow the design of **cellular structures with novel integrated contact mechanisms** that provide **local stress relief** under high loads. They are capable of ultimate strains exceeding 10%, while bulk ceramic materials have high strength, but low strain at failure (0.2-1%).
- Using **multiple materials** (e.g. **ceramic-metal** combination), these contacts also introduce new thermal conduction pathways and provide a novel potential avenue to **passive thermal switches**.
- When the “hot side” of the thermal base plate is **below a threshold temperature**, the base plate is in a **thermally-insulating** state, associated mainly with ceramic parts of the C3M based structure.
- As the temperature of the “hot side” increases **above threshold value**, the C3M based structure expands and **internal contact** is made between conducting members, dramatically **increasing the thermal conductivity** of the base plate. This conductivity is maintained at higher temperatures.



metal/ceramic parts made by  
“lost mold, rapid infiltration  
forming” (LM-RIF) process





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*Sensing, Precognition & Diagnosis;*

*Multifunctional Design of Autonomic Systems;*

*Multifunctional Design of Reconfigurable Systems;*

*Self-Healing & Remediation;*

*Self-Cooling & Thermal Management;*

***Energy Management for Self-Sustaining Systems***

*Actuation & Threat Neutralization;*

*Engineered Nanomaterials*

## **PI's & Co-PI's:**

**Max Shtein (U Mich) #**

**Henry Sodano (U FL)**

**Dan Inman (VA Tech)**

**Sven Bilén (Penn St U)**

**Michael Strano (MIT)**

**Greg Carman (UCLA)**

**Wonbong Choi (FL Int'l U)**

**Hugh Bruck (U MD)**

**Gleb Yushin (GA Tech) ^**

**Minoru Taya (U WA)\***

**Paolo Feraboli (U WA)\***

**Martin Dunn (U CO)\***

**Kurt Maute (U CO)\***

**Se-Hee Lee (U CO)\***

**Tom Hahn (UCLA)\***

**Dan Inman (VA Tech)\***

**Ioannis Chasiotis (UIUC)\***

**Michael Durstock (AFRL/RXBN)**

**Benji Maruyama (AFRL/RXBN)**

**John Coggin (Prime Photonics) +**

**Nersesse Nersessian (MAPCo) +**

**Anuncia Gonzalez (Lynntech) +**



# 2012 AFOSR SPRING REVIEW



NAME: B. J. ...

BRIEF DESCRIPTION:

Basic science research into future technologies

LIST OF SUBJECTS:

Fundamental

Life Prediction

Sensing, Feedback

Multifunctional

Multifunctional

Self-Healing

Self-Cooling

**Energy Materials**

Actuation

Engineered

**Subject:**  
*Energy Harvesting Textile Composites*  
*Active Structural Fibers for Multif'l Composites*  
*Vibration Suppression and Energy Harvesting*  
*Energy Harvesting Using Electrodynamic Tethers*  
*Environmental Hydrocarbon Harvesting Via CNT*  
*Nanoscale Based Thermal Energy Harvesting*  
*Flexible Battery of Graphene-CNT Hybrid*  
    > *Integrated Solar Cells for MAV Wings*  
    < *Multifunctional Mg-Li Alloy Nanocomposites*  
    < *Energy Harvesting/Storage System Integration*

**Subject:**

**PI's & Co-PI's:**

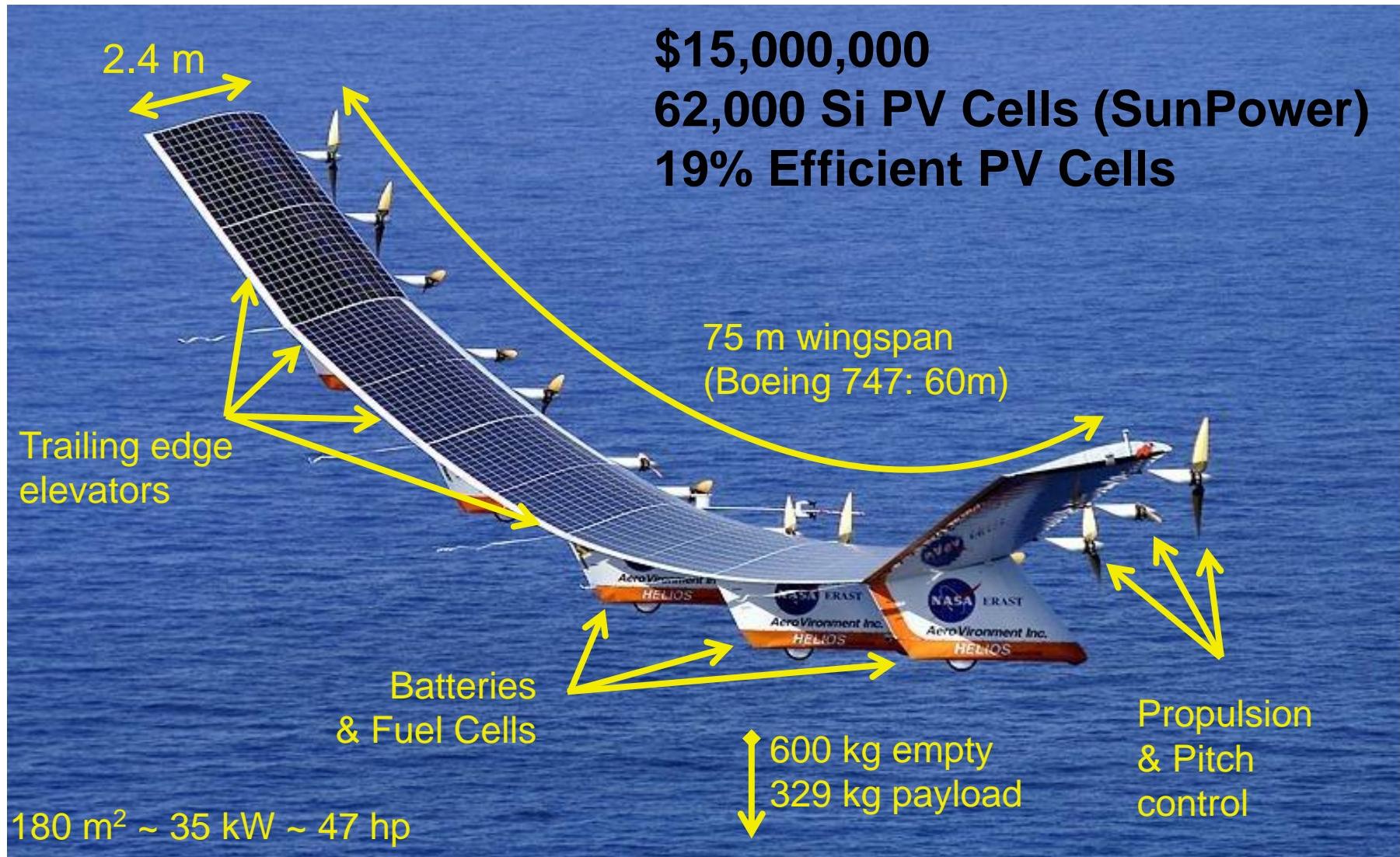
*Max Shtein (U Mich) #*  
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*Anuncia Gonzalez (Lynntech) +*

> *New*; < *Concluded*

# *PECASE*; ^ *YIP*; \* *MURI*; + *STTR*



# NASA “HELIOS”

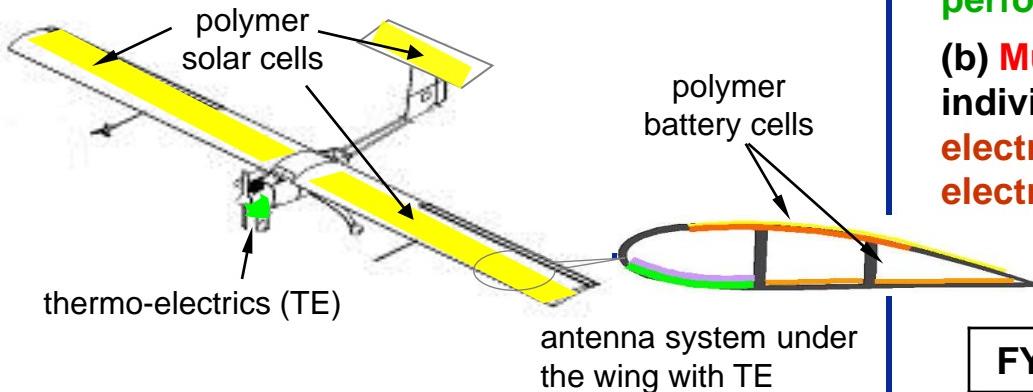


# INTEGR'D ENERGY HARVESTING (U WA/U CO/UCLA/VT: Taya)



## Objective:

To develop “self-powered” load-bearing structures with **integrated energy harvest/storage capabilities**, and to establish new **multifunctional design rules** for structural integration of energy conversion means.



## DoD Benefit:

Self-powered load-bearing structures with integrated energy harvest/storage capabilities will provide meaningful **mass savings** and **reduced external power requirements** over a wide range of defense platforms including **space vehicles, manned aircraft, unmanned aerial vehicles, and ISR systems**.

## Technical Approach:

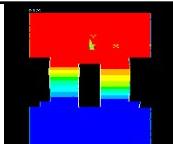
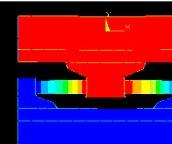
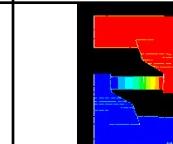
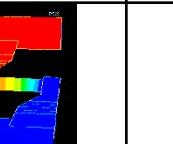
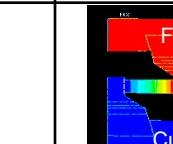
- (a) A combination of experimental and analytical techniques are employed to advance the **efficiency** of the energy conversion means (as an integral part of **load-bearing** structures) and to optimize their multifunctional performance and ability to cover larger areas.
- (b) **Multifunctional composites** are created with individual layers acting as **photovoltaic/thermo-electric/piezoelectric** power harvesting and **electrochemical** power storage elements.

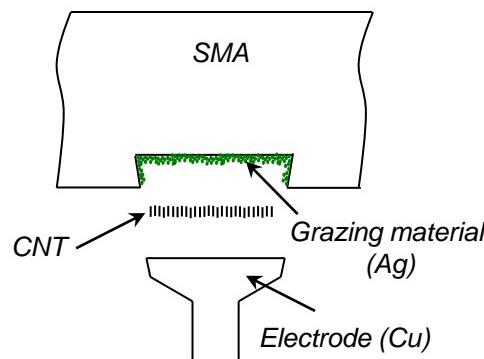
## Budget:

\$K	FY06	FY07	FY08	FY09	FY10	FY11
	693,335	1,169,560	1,180,608	1,219,324	1,179,991	568,571

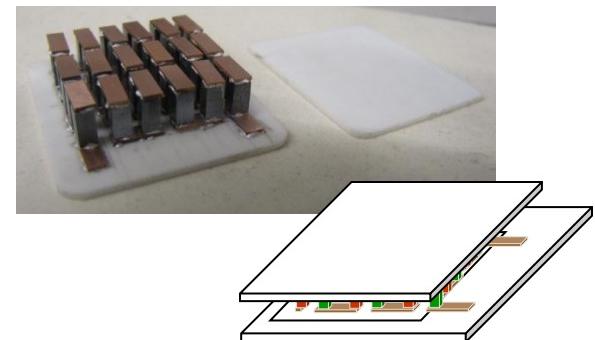
## Major Reviews/Meetings:

- 29 August 2007: Seattle, WA
- 5 August 2008: Boulder, CO
- 11 August 2009: Blacksburg, VA
- 18 August 2010: Los Angeles, CA
- 5 August 2011: Arlington, VA

TE design	Phi TE	Linear TE	Linear TE w/ FGM and shrink-fit (1.25mm)	Linear TE w/ FGM and shrink-fit (2.5mm)	Linear TE w/ FGM and shrink-fit (2.5mm)
Analysis results					
Generated temperature gap across TE element (deg C)	338	344	344	346	394
Maximum normal stress on electrode (Mpa)	-1100	-1200	-535	-591	-642
Maximum shear stress on electrode (MPa)	146	617	329	311	337
Maximum shear stress on TE element (MPa)	125	71	34	43	56
Power density (W/cm <sup>2</sup> )	<b>0.80</b>	<b>0.87</b>	<b>0.87</b>	<b>0.89</b>	<b>1.15</b>
Module efficiency (%)	<b>12.8</b>	<b>13.3</b>	<b>13.3</b>	<b>13.4</b>	<b>14.8</b>



- **n-type:  $Mg_2Si_{0.96}Bi_{0.03}In_{0.01}$**
- **p-type:  $Si_{0.93}Ge_{0.05}B_{0.02}$**
- Heat source side: Fe-SMA
- Heat exhaust side: Cu-SMA
- CNT in grazing material gives:
  - ✓ locking Ag
  - ✓ reducing the creep strain



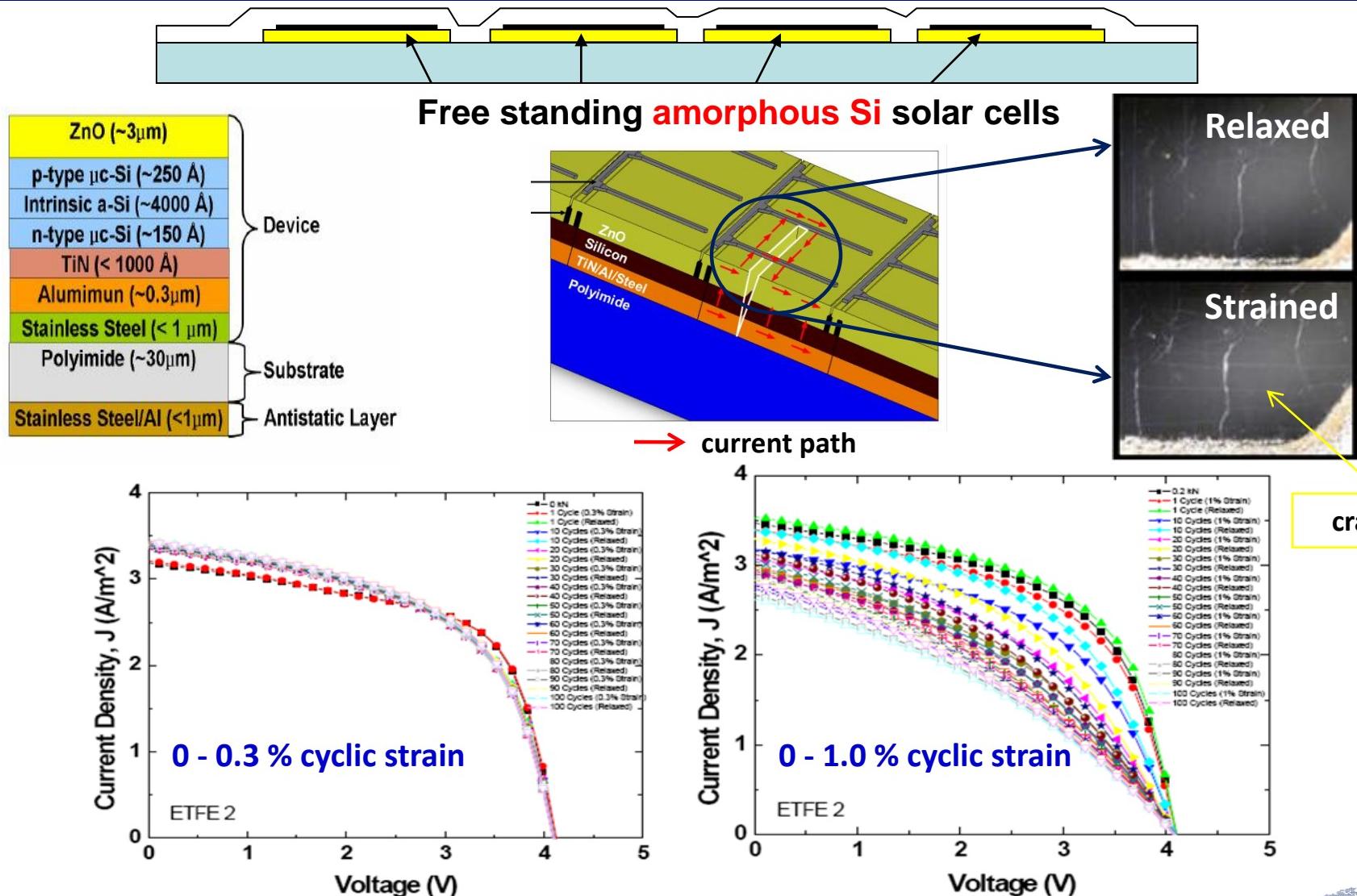
# Comparison of Solar Cells for Structural Integration



	Monocrystalline Silicon Solar Cell	Amorphous Silicon Solar Cell
Tensile Loading	Breaks at <b>0.23 %</b> tensile strain	Works well at <b>1.6 %</b> tensile strain. Composite laminates breaks around 1.5 % strain.
Fatigue Loading	N/A	Works well at fatigue cycle of 0.3 % strain
Efficiency	<b>23 %</b>	12 %
Price	High (200 um thick c-Si needed)	Low (about <b>1 um</b> thick a-Si needed)
Sample		

	Cu(In,Ga)Se <sub>2</sub> Solar Cell	Dye Sensitized Solar Cell
Pros	<b>Highest efficiency</b> among thin film solar cells	<b>Cheapest</b> among thin film solar cells
Cons	Degrades with <b>humidity</b> ; manufacturing generates very toxic gases to the environment.	Unstable efficiency; extremely <b>corrosive</b>

# Solar Cells Under Fatigue

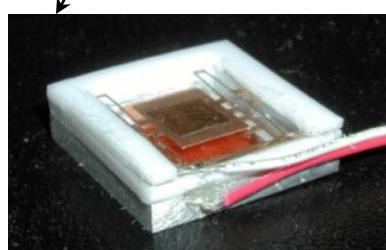
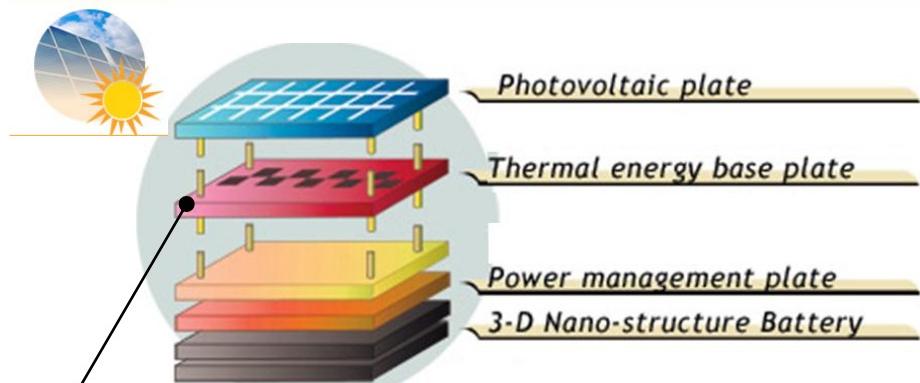




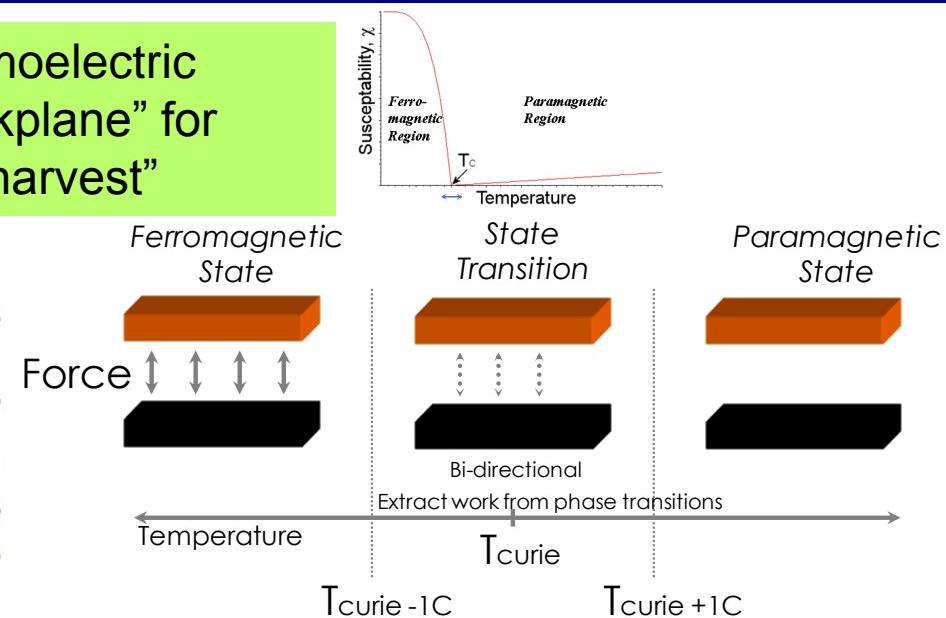
# STTR' 10: HYBRID ENERGY HARVEST



- Pairing solar panels with magneto-thermoelectric power generator as “active thermal backplane” for solar panel cooling and “hybrid energy harvest”



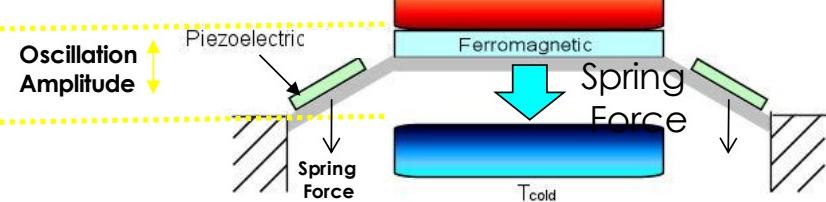
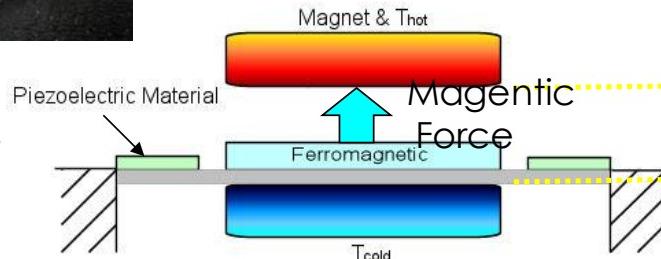
magneto-  
thermoelectric  
power generator  
(STTR'07)



## Ferromagnetic State (Cooling)

Bi-Directional

## Paramagnetic State (Heating)





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*Self-Cooling & Thermal Management;*  
*Energy Management for Self-Sustaining Systems;*  
***Actuation & Threat Neutralization;***  
*Engineered Nanomaterials*

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John Shaw (U Mich)  
**Patrick Mather (Syracuse U)**  
H. Jerry Qi (U CO)  
Martin Dunn (U CO)  
**Benjamin Shapiro (U MD)**  
Elisabeth Smela (U MD)  
**Shiv Joshi (NextGen)**  
Sharon Swartz (Brown U)  
Nakhiah Goulbourne (VA Tech)  
**Minoru Taya (U WA)**  
Frank Ko (U Brit Columbia)  
**Aaron Dollar (Yale U) ^**  
**A. John Hart (U Mich) ^**  
Xin Zhang (Boston U)  
**C. T. Sun (Purdue U)**  
**Thomas Siegmund (Purdue U)**  
**Anna Balazs (U Pitt)**  
**Nicole Zacharia (Texas A&M)**  
**Richard Vaia (AFRL/RXBN)**  
**Greg Reich (AFRL/RBSA)**

**^ YIP**



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Engineered

- Subject:**
- < **Cellular Shape Memory Structures**
  - < **Reversible Shape Memory Polymer Composites**
  - < **Electroosmotically Actuated Shape Change**
  - Ultra-Maneuverable Bat Technologies**
  - Bio-inspired Design of Reconfigurable Structures**
  - Active Cells for Multifunctional Structures**
  - Morphing CNT Microstructures**
  - Metamaterial Enhanced MEMS**
  - Acoustic Metamaterials w Local Resonance**
  - Macroscale Meta-Materials**
  - Active Materials w Sensory & Adaptive Capabilities**
  - > **Mechano-Responsive Polymer Systems**
  - Mechanically-Responsive Polymers**
  - Thermally-Activated Reconfigurable Systems**

> New; < Concluded

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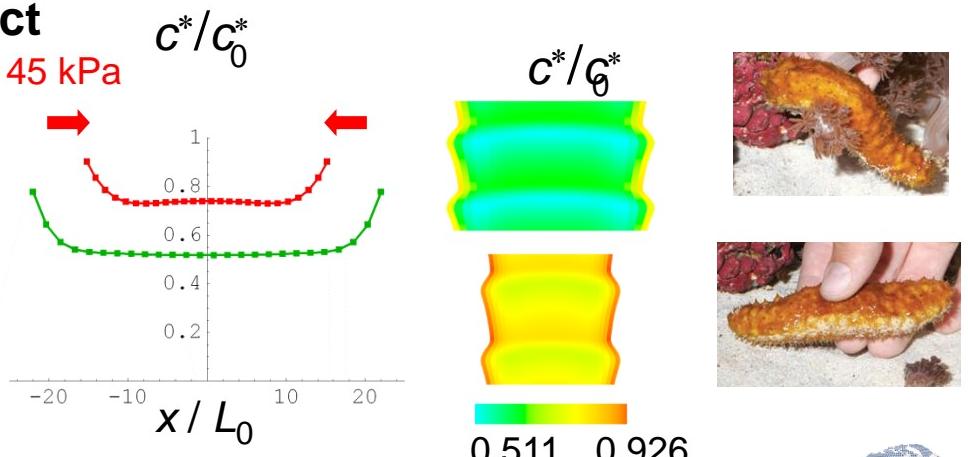
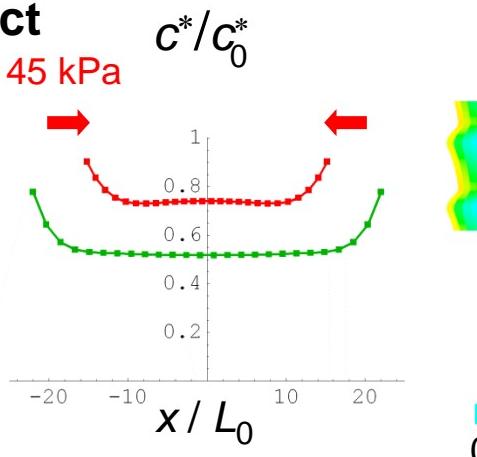
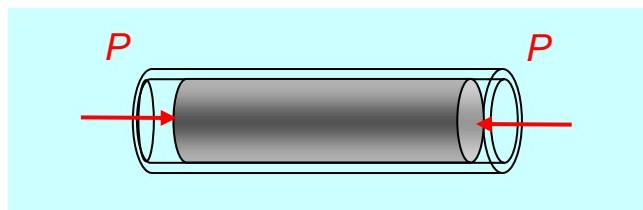
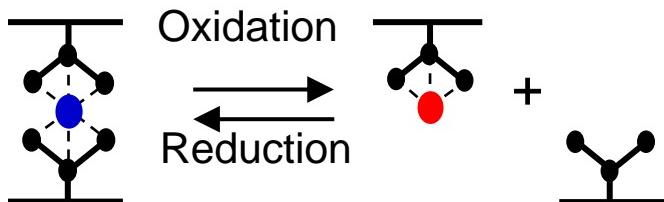
^ YIP



# DESIGNING SELF-REINFORCING MATERIALS (*U Pitt: Balazs*)



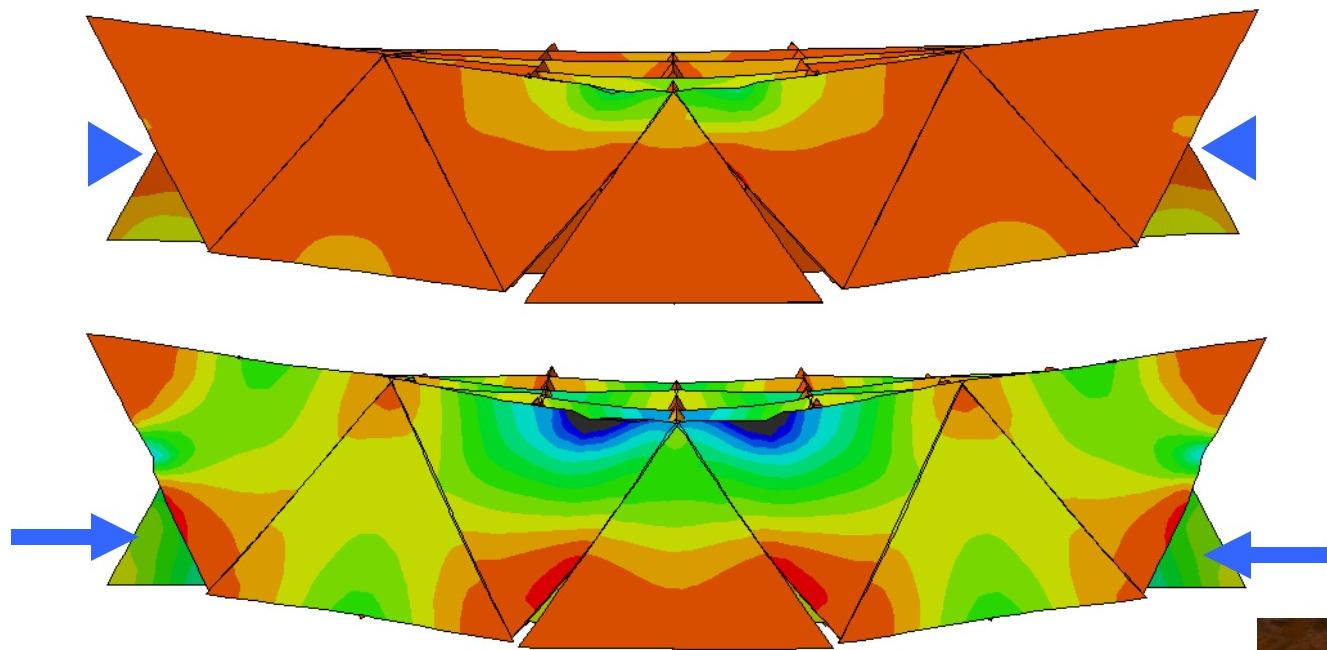
- Developed model to describe BZ gels with chemo-responsive X-links
  - Modified Oregonator model
  - $f$  – dependent complex formation
  - Time-dependent elastic contribution
- Studied response to steady and periodic compression in 1D model
- Mechanical impact increases X-link density
  - Self-reinforcing material
  - Stiffens in response to impact



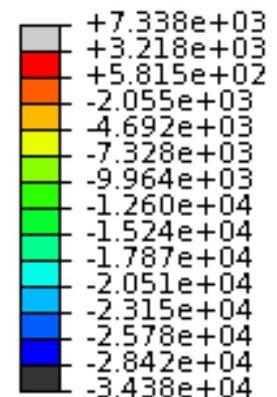
V.V. Yashin, O. Kuksenok, A.C. Balazs,  
*J. Phys. Chem. B* 2010, 114(19), 6316.



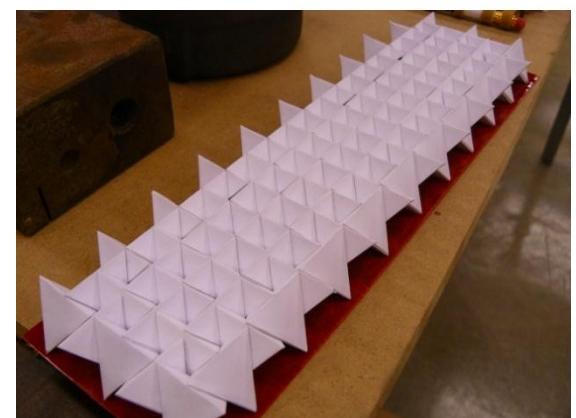
# TOPOLOGICAL INTERLOCKING (Purdue U: Siegmund)



In-plane Stress



- Confinement changes translate in change on contact conditions
- Large confinement leads to smaller opening and more resistance to load
- Retain damage tolerance in the high stiffness regime





# 2012 AFOSR SPRING REVIEW



NAME: B. L. ("Les") Lee

## BRIEF DESCRIPTION OF PORTFOLIO:

*Basic science for integration of emerging materials into future Air Force systems requiring multi-functionalities*

## LIST OF SUB-AREAS:

*Fundamentals of Mechanics of Materials;  
Life Prediction (Materials & Micro-devices);  
Sensing, Detection & Diagnosis;  
Multifunctional Design of Autonomic Systems;  
Multifunctional Design of Reconfigurable Systems;  
Self-Healing & Remediation;  
Self-Cooling & Thermal Management;  
Energy Management for Self-Sustaining Systems;  
Actuation & Threat Neutralization;  
Engineered Nanomaterials*

## **PI's & Co-PI's:**

**Jimmy Xu (Brown U)**  
**Erik Thostenson (U Del)^**  
**Frank Ko (U Brit Columbia)\***  
**Jeff Baur (AFRL/RXBC)**  
**Nancy Sottos (UIUC)**  
**Vikas Prakash (Case Western)**  
**Ajit Roy (AFRL/RXBT)**  
**Michael Strano (MIT)**  
**Greg Carman (UCLA)**  
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**Gleb Yushin (GA Tech)^**  
**Se-Hee Lee (U CO)\***  
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**A. John Hart (U Mich)**  
**Richard Vaia (AFRL/RXBN)**  
**Ray Baughman (U Texas Dallas)**  
**Nicholas Kotov (U Mich)**  
**Mrinal Saha (OK St U)**  
**Tsu-Wei Chou (U Del)**  
**Yuntian Zhu (NCSU)**  
**Alexander Bogdanovich (NCSU)**  
**Philip Bradford (NCSU)**



# 2012 AFOSR SPRING REVIEW



NAME: B. J. ...

BRIEF DESCRIPTION

Basic science research into future technologies

LIST OF SUBJECTS

Fundamental Materials

Life Prediction

Sensing, Detection

Multifunctional Materials

Multifunctional Composites

Self-Healing Materials

Self-Cooling Materials

Energy Management

Actuation & Control

Engineering Applications

## Subject:

- Thermal Signature Reduction & EMI Shielding*
- Nanocomposites for Sensing & Actuation*
- Bio-inspired Intelligent Sensing Materials*
- Embedded Sensors & Actuators for MAV*
- Interfacial Self-Healing in Composites*
- CNT Based Thermal Interface Materials*
- Carbon Fiber Morphology for Thermal Materials*
- Environmental Hydrocarbon Harvesting Via CNT*
- Nanoscale Based Thermal Energy Harvesting*
- Flexible Battery of Graphene-CNT Hybrid*
- Multifunctional Mg-Li Alloy Nanocomposites*
- Energy Harvesting/Storage System Integration*
- Nanomaterials for Structural Batteries*
- Morphing CNT Microstructures*
- Mechanically-Responsive Polymers*
- Artificial Muscles for Large Stroke & High Force**
- < **Layer-by-layer Processing of CNT Composites**
- < **Hierarchical Structures of CNT Composites**
- Thin Flexible CNT Composites**
  
- > **Shear Pressed CNT Sheets for Strain Sensing**

## PI's & Co-PI's:

- Jimmy Xu (Brown U)**
- Erik Thostenson (U Del)<sup>^</sup>**
- Frank Ko (U Brit Columbia)\***
- Jeff Baur (AFRL/RXBC)**
- Nancy Sottos (UIUC)**
- Vikas Prakash (Case Western)**
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- Philip Bradford (NCSU)**

> New; < Concluded

<sup>^</sup> YIP; \* MURI



# CNT YARNS FOR ARTIFICIAL MUSCLES (*UT Dallas: Baughman*)

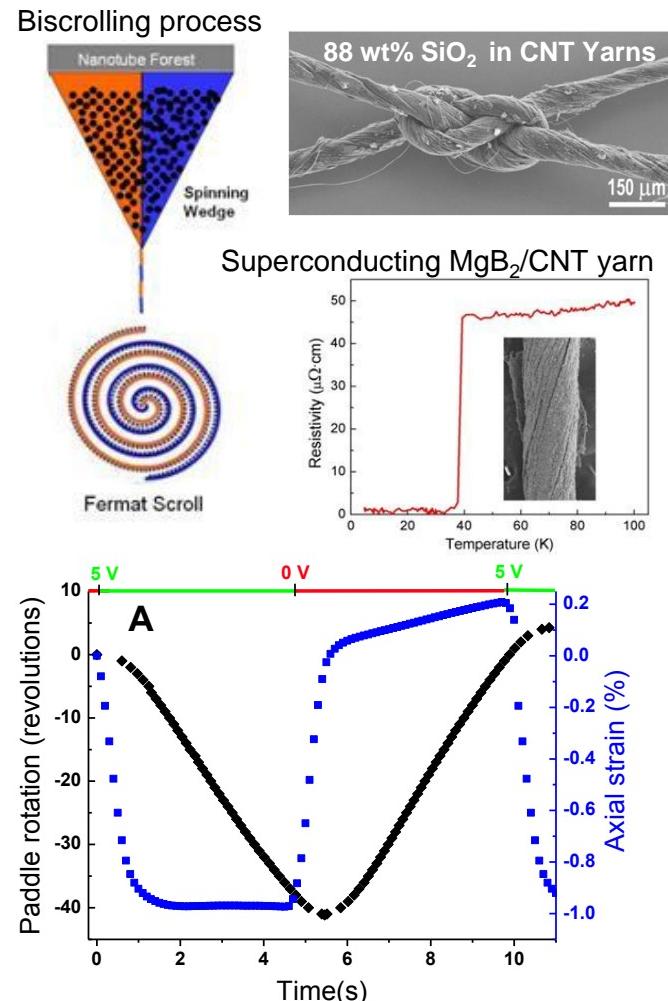


*"Biscrolling Nanotube Sheets and Functional Guests into Yarns"*, *Science* 331, 51 (2011).

- **Weavable, sewable, braidable** and **knottable** carbon nanotube (CNT) **yarns** that can contain over 92 wt% of **functional guest powders** are made by twist insertion in a guest/CNT sheet stack.
- Demonstrated use of these **"biscrolled" yarns** as **battery/fuel cell electrodes** and as **superconductors**.

*"Torsional Carbon Nanotube Artificial Muscles"*, *Science* 334, 494 (2011).

- **Tensile** and **torsional actuation** results from **yarn volume change** caused by **ion influx** to compensate **electronically injected charge**. Torsional rotation per actuator length was 1000 times that of prior-art torsional actuators.
- The actuating yarn electrode can accelerate an 1800 times heavier paddle up to 590 revolutions/min in 1.2 s and provide similar gravimetric torque and mechanical power generation per yarn weight as for large electric motors. **Microfluidic** application was demonstrated.



Torsional and tensile actuation for electrochemically driven twist-spun yarns



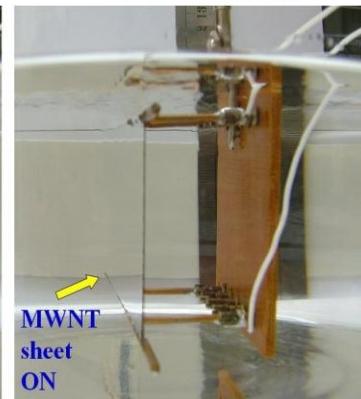
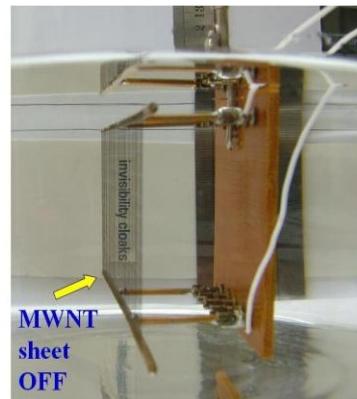
# MIRAGE EFFECT OF CNT SHEET (UT Dallas: Baughman)



"Mirage Effect from Thermally-modulated Transparent Carbon Nanotube Sheet",  
Nanotechnology **22**, 435704 (2011).

- **Electrically conducting sheets**, which are drawn from forest-like arrays of carbon nanotube (CNT), can be used as **transparent**, rapidly **thermally switchable mirage cloaks** and as inexpensive optical scanners.
- This **invisibility for light** oblique to the CNT sheet is caused by the **mirage effect**, in which a thermally generated **refractive index gradient** bends light array from an object.
- Extremely **low thermal capacitance** and **high heat transfer ability** of CNT sheets enable high frequency modulation of sheet temperature over a wide range, thereby providing a sharp, rapidly changing gradient of refractive index in surrounding liquid or gas.

Time Magazine's issue  
on 50 Best Inventions  
of 2011



Cloaking



# BIO-INSPIRED SYSTEMS: BEYOND CURRENT VISION



## VISION: EXPANDED



Biomimetics

Design for Coupled  
Multi-functionality

Nano-materials

Multi-scale  
Model

Micro- & Nano-  
Devices

Manufacturing Sci

Neural Network &  
Information Sci

### AUTONOMIC AEROSPACE STRUCTURES

- Sensing & Precognition
- Self-Diagnosis & Activation
- Self-Healing
- Threat Neutralization
- Self-Cooling
- Self-Powered

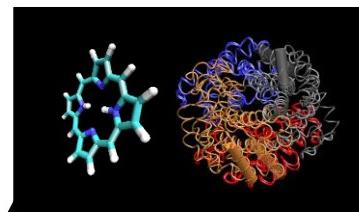
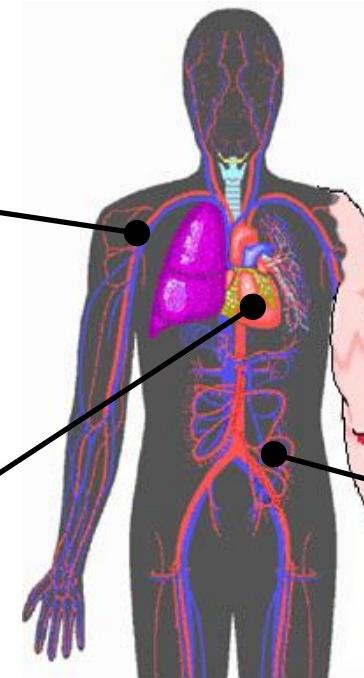
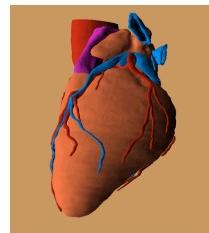


## FUNCTIONS OF INTEREST



### *Self-Regulating Function*

Active Regulation



### *Self-Generating Function*

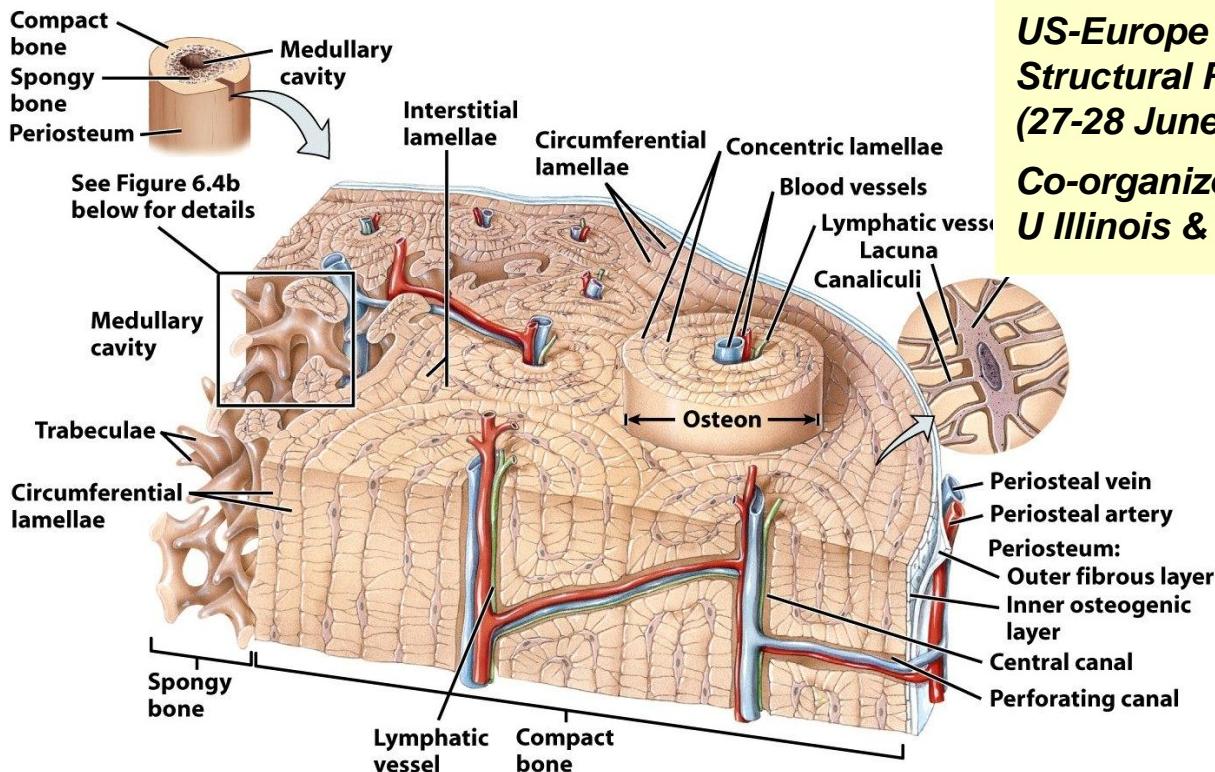
Mesoporous Networks



# Design by Nature: BONE REMODELING



**Resorption vs Ossification;** 4~20% renewal per year;  
**Subjecting a bone to stress will make it stronger**



**US-Europe Workshop on  
Structural Regeneration  
(27-28 June 2012, Venice)**

**Co-organized by AFOSR, ARO,  
U Illinois & Max Planck Inst.**

**Fig. 6-4a Anatomy and Physiology: From Science to Life © 2006 John Wiley & Sons**



# ENGINEERED DEVICES: BEYOND CURRENT VISION



## Traditional Transducer Materials

	Shape Memory Alloy	Piezoelectric Ceramics and Polymers	Ionomeric Polymer Materials	
Device/ System				
Material				
Transduction Mechanism	Material Transformation	Dipole Rotation	Ion Migration	Increasing length scale



Center for Intelligent Material Systems and Structures  
at Virginia Polytechnic Institute and State University

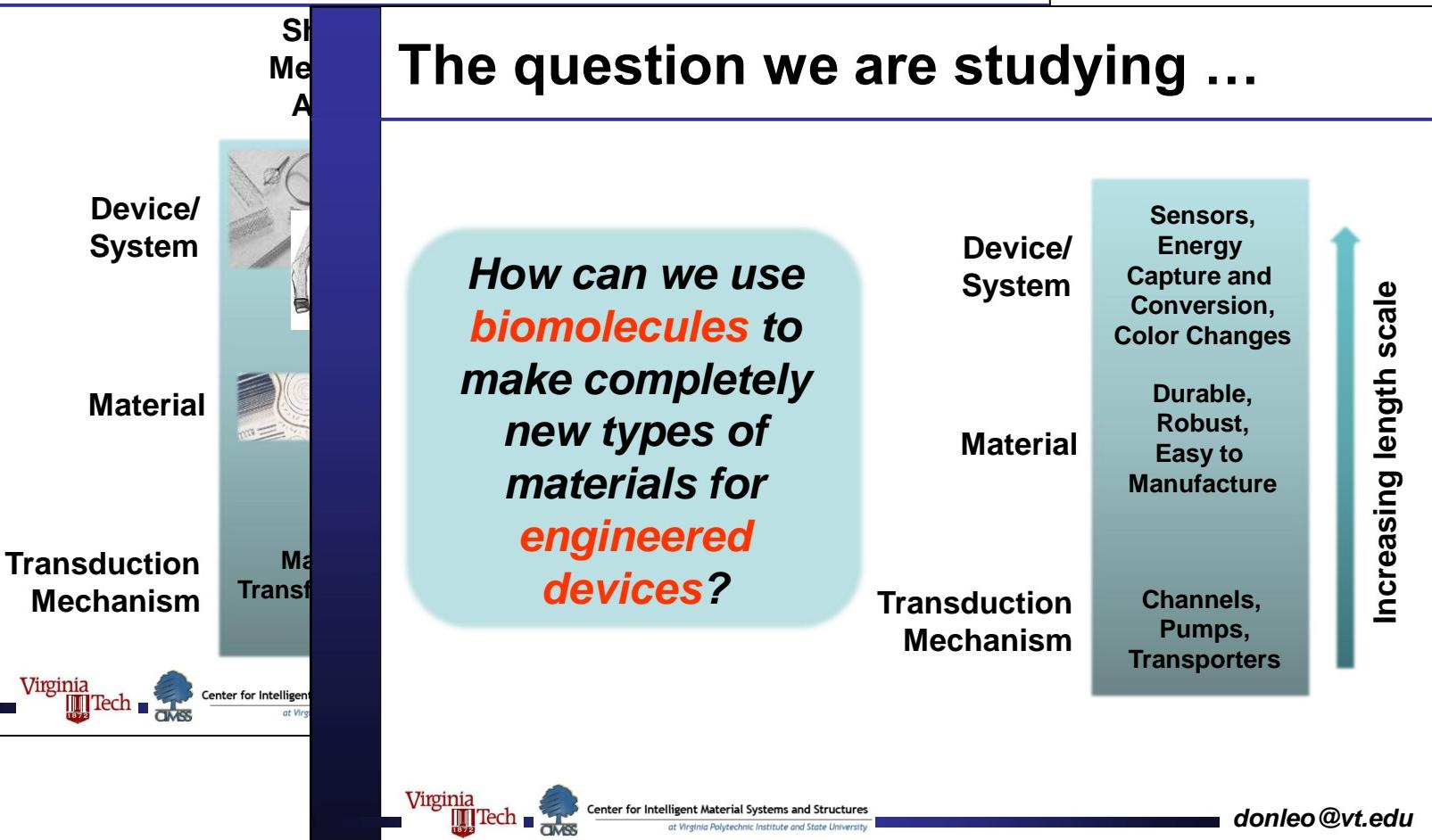
[donleo@vt.edu](mailto:donleo@vt.edu)



# ENGINEERED DEVICES: BEYOND CURRENT VISION



## Traditional Transducer Materials





# SUMMARY



- The program is fully focused on the establishment of advanced multi-functional aerospace structures.
- A major progress has been made in pursuing a new **vision** for **autonomic/reconfigurable systems** and providing research support for baseline multifunctional materials and microdevices.
- Multi-disciplinary research initiatives are concluded successfully for “*self-healing*,” “*structurally integrated energy harvest/ storage capabilities*,” “energy harvesting from aerospace environment,” and “*load bearing antennas*.”
- Three initiatives are in progress for “*neurological system inspired sensory network*” (MURI ’09), “*reconfigurable multi-functional structures*” (DCT’09) and “*high-rate deformation*” (CoE’12).
- New initiatives are planned for “*biomolecular autonomic material systems*,” “*hybrid energy harvesting*” and “*neutralization of threats*” in collaboration with AFRL/AFOSR colleagues.